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FINAL PROJECT REPORT

CONSUMER RESPONSE TO PLUG-IN HYBRID ELECTRIC VEHICLES:

Vehicle Design Priorities, Driving and Charging Behavior, and Energy Impacts

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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ABSTRACT

Whether plug-in hybrid electric vehicles provide energy and emissions benefits beyond hybrid electric vehicles depends on relationships among plug-in hybrid electric vehicle designs, driving patterns, and charging behaviors. This report summarizes two research projects that explore these relationships. The first solicits interest in plug-in hybrid electric vehicles from a nationally representative sample of new-car-buying households and uses data from their one-day diary to explore driving and charging patterns. The second provided plug-in hybrid electric vehicle conversions to households in Northern California for four to six weeks. Interest in plug-in hybrid electric vehicle designs were elicited from demonstration drivers in the same manner as the national sample; their driving and charging behaviors were also measured. A key difference between the two groups is that the national sample did not require home charging capabilities; whereas plug-in hybrid electric vehicle drivers for the demonstration were selected because they could charge a vehicle at home. From the national sample, researchers estimate that nearly half of new-car-buying households could charge a vehicle at home. Both groups design plug-in hybrid electric vehicles that differ markedly from those typically assumed by expert analyses. Much of the estimated greenhouse gas emission benefits from combining data on vehicle designs, driving, and charging are due to the efficiency improvements of hybridizing the drivetrain. Across the households with experience driving and charging a plug-in hybrid electric vehicle, time-of-day charging behaviors varied widely; while much of the observed charging occurred during times of peak electricity demand. Most plug-in hybrid electric vehicle drivers relied on metrics related to gasoline consumption to represent the added value of the PHEV. These results indicate consumers can be engaged in electrifying their daily mobility but will require changes in vehicle design, charging infrastructure, and information to fully realize the benefits of plug-in hybrid electric vehicles.

Keywords: Consumer, demand, all-electric, charge sustaining, charge depleting, plug-in hybrid electric vehicle, hybrid electric vehicle, charge, charging

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EXECUTIVE SUMMARY

Introduction

Potential benefits of plug-in hybrid electric vehicles (PHEVs) are derived from replacing some gasoline with electricity, thus potentially reducing the costs, petroleum use, air pollution, and greenhouse gas emissions associated with driving. However, the dual fuel potential of plug-in hybrid electric vehicles presents inherent uncertainty to policy makers, automakers, electric utilities, researchers, and other interest groups. Predictions of gasoline and electricity use, as well as the associated emissions, depend on the interactions between plug-in hybrid electric vehicle design and consumers' driving and charging behaviors. Due to a lack of observed behavioral data, plug-in hybrid electric vehicle impact and market analyses have relied on assumptions about such behaviors or attempts to describe them by proxy from databases of travel patterns and housing stocks.

Purpose

This research stimulates and reports consumer consideration of plug-in hybrid electric vehicles—to replace assumptions about consumers with actual preferences and experiences. Stimulating consumer consideration is necessary to answer the question, "Why would consumers buy plug-in hybrid electric vehicles?" This question logically precedes the query, "Who will buy them?"

The primary research reported here is based on two projects within a larger electric-drive vehicle consumer research agenda:

- Nationwide survey of new-car-buying households, with representative oversampling of California and cities and towns along the Interstate-80 corridor in Northern California.
- Household PHEV Demonstration and Market Research Project, in which households in north-central California were provided an opportunity to drive a plug-in hybrid electric vehicle for four to six weeks. Results from the first 34 households are reported here.

Objectives

The nationwide survey of new car buyers addressed four research questions:

- How aware are U.S. new-car-buying households of electric-drive vehicles?
- How many of these households have regular access to vehicle charging?
- Which PHEV performance capabilities appeal to them?
- What energy effects (gasoline and electricity) can researchers anticipate with significant plug-in hybrid electric vehicle adoption, based on consumers' plug-in hybrid electric vehicle design preferences?

To answer these questions, researchers collected data through a Web-based survey of new vehicle buying households in the United States. These data were supplemented with a one-day diary of their vehicle driving and parking patterns. The sample was representative of national new car buyers with intentional oversampling of California and Northern California in which a Household PHEV Demonstration and Market Research Project would be conducted.

The Household PHEV Demonstration and Market Research Project addressed the following questions:

- What are the plug-in hybrid electric vehicle designs created by Household PHEV Demonstration and Market Research Project households?
- What are the charging behaviors of the project households, and how do driving behaviors influence charging behaviors?
- Given that project participants are driving one specific incarnation of what a plug-in hybrid electric vehicle can be, what are the effects on their transportation energy use?

To answer these questions, researchers collected data from households who drove a PHEV. Toyota Priuses were purchased and converted to plug-in operation. These PHEV-conversions are best described as operating in a manner that more or less continuously blends electricity and gasoline while the battery is being discharged. While the supplemental battery is discharging, far more electricity is being used than in a conventional Prius. After the battery is discharged, the vehicle runs solely on gasoline, as do all hybrid vehicles.

The plug-in hybrid electric vehicle conversions were placed in households in Northern California. The realized sample is a reasonable match for the national survey sample, with three important qualifications:

- For the demonstration, researchers oversampled preexisting hybrid vehicle owners. Even so, preexisting hybrid owners are a small part of the demonstration sample.
- The demonstration sample contained some households that are not new car buyers as defined for the national survey.
- Plug-in hybrid electric vehicle demonstration drivers were selected in part because they could charge a vehicle at home. No requirement to be able to charge a car at home was placed on the national sample, since one of the questions to be answered by that study was how many households can charge a vehicle at home.

During the households' plug-in hybrid electric vehicle trial use period, researchers collected data on travel, vehicle charging and refueling, performance of the vehicle, and participants' response to the plug-in hybrid electric vehicle technology. Researchers collected data directly from the vehicle using on-board data systems, as well as from multiple in-home interviews, online questionnaires based on those administered to the national new car buyer sample, and fueling logs.

Essential to both the national survey and the demonstration task was the development of an interactive vehicle design game in which households could design their next new vehicle as a plug-in hybrid electric vehicle. The game did not include electric vehicles or hybrid vehicles, unless a household indicated that it was already interested in such a vehicle as its next new vehicle. The design game allowed players to manipulate the following performance parameters of plug-in hybrid electric vehicles: 1) charging time, 2) distance the vehicle could be driven before the battery discharged, 3) whether the vehicle ran on only electricity while discharging the battery or used both electricity and gasoline, 4) if the latter, then in what proportion gasoline and electricity were used (by manipulating gasoline fuel economy), and 5) gasoline-only fuel economy after the battery was discharged. All households played these games with low, medium, and high vehicle price conditions. It is through these design game results that researchers have drawn conclusions about why people may buy plug-in hybrid electric vehicles, and who may buy them

Conclusions

The essential lesson of the two research projects reported here is that allowing consumers into the design and use processes of new motor vehicle drive-trains and fuels produces different performance capabilities and different use patterns than expert analyses have typically assumed and thus very different estimates of private, social, and environmental effects. Additional conclusions from the work are as follows:

- Among all three groups of survey respondents, the national, California, and Northern California samples of new car buyers, about half reported they parked a car at home within 25 feet of a 110 volt household electrical outlet. This was the research team’s basic measure of access to home charging for a plug-in vehicle.
- Plug-in hybrid electric vehicles that sampled car buyers design differ markedly from those typically assumed by expert analyses across all three groups of survey respondents and the PHEV demonstration project participants. At present, all-electric driving is not widely valued by any sample of households. High gasoline fuel economy both while discharging the battery and continuing until the battery is charged again is far more likely to be incorporated into households’ PHEV designs.
- Given the households’ plug-in hybrid electric vehicle designs, driving, and charge access, much of the estimated greenhouse gas emissions benefits are due to the efficiency improvements of hybridizing the drivetrain. Smaller additional improvements are due to the displacement of gasoline by electricity from the electrical grid.
- Across the households with actual plug-in hybrid electric vehicle driving experience, time-of-day charging behaviors varied widely. Much of the observed charging occurred during times of peak electricity demand. This behavior was unmitigated by time-of-day tariffs or supporting technologies, such as timers.
- Most plug-in hybrid electric vehicle drivers relied on metrics related to gasoline consumption, such as miles per gallon or days between gasoline-refueling, to represent the added value of the vehicle.

Taken in total, these results indicate that 1) consumers can be engaged in electrifying their daily travel, and 2) they will require changes in vehicle design, charging infrastructure, and information to fully realize the potential benefits of plug-in hybrid electric vehicles.

The research questions posed above are answered below.

1*. How aware are U.S. new car buying households of electric-drive vehicles?*

Awareness of plug-in hybrid electric vehicles is generally low, and there is potential for the language typically used by experts to create confusion among consumers.

- Among national new car buyers, their stated familiarity with vehicle technologies corresponded to the potential for real-world experience. High levels of familiarity were most common for conventional gasoline vehicles, followed in descending order by hybrid vehicles, electric vehicles, and plug-in hybrid electric vehicles: 31 percent claimed to have high or moderate familiarity with PHEVs.
- The vast majority of respondents understood that conventional gasoline vehicles could use only gasoline while electric vehicles can use only electricity.
  - But things are less clear for hybrids and plug-in hybrid electric vehicles. Poor levels of understanding emerged as responses show that 25 percent of the respondents thought that a plug-in hybrid electric vehicle could use only electricity, and 68 percent of respondents thought that a hybrid electric vehicle could be refueled either with gasoline or by plugging into an electric outlet.

This demonstrates enormous potential for misunderstanding the characteristics of plug-in hybrid electric vehicles among new vehicle buyers, the majority of whom seem to think that currently available hybrids can (or must) be plugged into the electricity grid. There is widespread confusion regarding electric-drive terminology and perhaps widespread misunderstanding of the functions, requirements, and benefits of different electric-drive technologies.

2. How many of these households have regular access to vehicle charging opportunities?

About half of the national sample of new car buyers identified a place where they could park and charge a vehicle. This estimate is one-and-a-half to three times higher than prior estimates, based on proxy measures of household vehicle ownership and housing characteristics.

- About 59.5 percent found at least one viable charge location during their 24-hour ordinary day; 52.4 percent identified one at their home.
  - Only among those living in single-family homes and those who have homes with attached garages did a majority identify a suitable place to park and charge a vehicle.
- About 45.8 percent of the sample of new car buyers in California parks their vehicle within 25 feet of an electrical outlet at home.
- About 45.6 percent of the Northern California sample has home charge access according to the definition above.

3. What PHEV design(s) currently appear to them?

Researchers have limited the discussion of plug-in hybrid electric vehicle designs to those 52.4 percent of households who could plausibly park and charge such a vehicle at their home. This was done to focus attention on a more plausible early market, such as people who do not face the additional cost or inconvenience of obtaining regular access to charging.

Within this more plausible early market subset, a majority favors a plug-in hybrid electric vehicle for their next new vehicle. However, the vehicles they design differ markedly from the all-electric designs widely assumed by analysts.

- The majority, 64.1 percent to 80.2 percent going from high- to low-price versions of the design game, would value plug-in hybrid electric vehicle capabilities in their next vehicle, meaning that they designed their next car as a plug-in hybrid electric vehicle.
- A substantial portion accepted the proffered base plug-in hybrid electric vehicle model, 26.5 percent in the low-price condition, and 38.8 percent in the high-price condition.
    - The base plug-in hybrid electric vehicle operates by using both gasoline and electricity while discharging its battery. The battery discharges within 10 miles; it would take eight hours to fully charge. It achieves an effective 75 miles per gallon (mpg) for the first 10 miles. Once the battery is discharged, the vehicle achieves a fuel economy that is 10 mpg higher than whatever conventional vehicle was the starting point for the design game, that is, whatever vehicle the household thought it might buy as its next new vehicle in the absence of plug-in hybrid electric vehicles.
- There is no evidence of strong interest in all-electric operation while the battery is being discharged. All-electric upgrades were incorporated into plug-in hybrid electric vehicle designs by 5.7 percent and 1.5 percent of respondents in the low- and high-cost conditions, respectively.

4. What energy impacts (gasoline and electricity) can be anticipated with significant PHEV adoption?

Researchers estimate total gasoline and electricity use as well as peak electricity demand and timing within a set of charging availability scenarios meant to represent potential boundary conditions, that is, where the entire market adheres to a selected condition, such as no regulation, enhanced workplace, or off-peak charging only. Researchers do this as an index of the potential for plug-in hybrid electric vehicles to affect gasoline and electricity use, assuming 1 million households buy plug-in hybrid electric vehicles for which designs are distributed as the distribution of designs created by the plausible early market households in the high price version of the design game.

- The scenario called plug and play, which assumes plug-in hybrid electric vehicle drivers charge whenever they parked their car within 25 feet of an electrical outlet, also assumes that there are no pricing mechanisms or technologies to divert charging to off-peak:

    - Most charging occurs at home, peaking at 6:00 p.m. at 596 megawatts (MW). This is half the peak demand of 1,200 MW (per million PHEVs) anticipated by some prior estimates using a similar procedure.
    - Gasoline use of the 1 million PHEVs is estimated to be half what it would have been if those million PHEVs had been conventional vehicles.
    - A large portion of this gasoline reduction—76 percent to 81 percent—is due to increases in fuel economy because of the hybrid drivetrain.
- The peak magnitude and timing of electricity demand for charging vary widely across charging scenarios.
    - The Enhanced Worker Charging Access scenario, in which workplace charging is added to those households who did not identify a place to park and charge a vehicle in their diary, increases overall electricity use by 34 percent relative to plugand play, with much of the additional charging occurring in the morning as drivers arrive at work.
    - The Off-Peak-Only scenario reduces electricity use from plug and play by 16 percent, largely due to the elimination of work and other nonhome charge opportunities that occur during peak hours.
        - The Off-Peak-Only scenario has the benefit of eliminating all electricity use during peak hours, with nightly demand balanced at 365 MW. The specific balancing strategy used in practice as part of off-peak charging would likely vary by electric utilities; the research team's scenario merely demonstrates the potential to shift and minimize peak demand.

5. What are the PHEV designs created by household PHEV demonstration and market research project households?

- After driving a PHEV for a few weeks, the majority of project drivers would value PHEV capabilities in their next vehicle.
- There is no evidence of strong interest in PHEVs with all-electric operation.
    - Seven plausible early market project participants (25 percent) were satisfied for their future PHEV to have the base performance offering (the same performance as the base PHEV in the survey samples games).
    - Among those who created higher cost designs, further fuel economy upgrades were included more often than other upgrades. All-electric upgrades were included by two households (7 percent) and four households (13 percent) in the higher and lower price conditions, respectively.
- A higher percentage of project drivers show more interest in a longer battery-assisted range than among the survey samples of new car buyers, but few showed an interest in going as far as 40 miles.

- Eleven project households (37 percent) designed a PHEV capable of 75 mpg for the first 10 miles, and 24 households (86 percent) designed a blended charge-depleting (CD) design, as opposed to all-electric, with a range of 20 miles or fewer.

- Notably, 67 percent of project PHEV drivers selected some variety of hybrid electric vehicle (HEV) and 40 percent selected a Toyota Prius, as their likely next new vehicle. These percentages are 2 to 3.5 times higher than those of the California and Northern California survey samples.

6. What are the charging behaviors of the project households,and how do driving behaviors influence charging behaviors?

The charging results reported in this context are from households who can charge at home, whose charging frequency is constrained by a general lack of away-from-home charging opportunities created by the lack of both physical infrastructure and social norms, but unconstrained by differential electricity prices or other controls. Data from a single week of each household's driving and charging are collected to create the summary evaluation.

- All instances of plugging the car into an electrical outlet do not result in charging the battery to full or full charges with the connotation of a fully discharged battery being returned to a full state of charge.

- The average number of plug-in events per weekday per household ranged from zero to 2.6 instances of plugging in per day.
    - Plugging-in occurs less frequently on weekend days. One-fourth of the sample did not plug-in their PHEV on either weekend day. The high end of the range was 1.5 times per weekend day.

- It was never the case on any weekday or weekend day that all the PHEVs would have been plugged in at one point in time.
    - Across weekdays, 60 percent to 75 percent of PHEVs were plugged in between midnight and 6 a.m.
    - The greatest day-to-day variation occurs on weekdays during present peak electricity demand between 5 p.m. and 9 p.m. as households differed in their end-of-day charging behaviors.
    - Fewer PHEVs would have been plugged in on weekend days at any given time of day than weekdays.

- Electricity demand to charge the vehicles did not approach the peak potential demand (if all vehicles had been charging at once) because all the PHEVs would not have been plugged in at the same time.
    - Peak power demand across all five weekdays was about half the potential peak.

- As with variation in the number of vehicles that would have been plugged in at any point in time, the greatest variation in electricity demand across weekdays would have started at 5 p.m. but would extend to midnight.
- Peak power demand on weekend days was roughly one-third what it would have been if all vehicles were charging at once.

7. Given that project participants are driving one specific incarnation of what a PHEV can be, what are the effects on their transportation energy use?

One measure of the energy effects of substituting electricity for gasoline in these PHEVconversions is the difference in (gasoline-only) fuel economy. Researchers describe these results first as the measure used by most demonstration participants.

- Across the group, the mean fuel economy while driving with the battery discharged was 44.7 mpg; the mean (gasoline-only) fuel economy while the battery was still charged and electricity was being used to help power the cars was 67.1 mpg.
  - Thus, the group mean increase in charge depleting CD versus charge sustaining is 49 percent.
- These group measures obscure tremendous variation across households.
  - The distribution of households' mean fuel economy improvements varied from 21 percent to 101 percent. Improvements of more than 70 percent are exceptions; 90 percent of households had improvements less than 71 percent and the median improvement was 46 percent.

While households used gasoline-only fuel economy as their measure of energy use, an integrated analysis of gasoline and electricity is essential to the question of whether PHEVs deserve societal sanctions. The analysis presented here is preliminary and partial. It is preliminary because researchers do not expect that the full range and variety of the relationships between travel and charging behavior on one hand and total energy use on the other have been observed among the project participants. Further, this analysis is preliminary because only one particular PHEV is analyzed. The analysis is partial because it is not a life-cycle analysis; researchers address only electricity out of the battery and gasoline out of the tank. The analysis is partial in that it addresses only the marginal difference made as the project households drove and charged a PHEV. Researchers compare households' actual total gasoline plus electricity consumption during their PHEV trial to the amount of gasoline they would have used had they driven their entire PHEV trial without charging.

- In total, the first 34 project participants drove the PHEV-conversions just greater than 33,000 miles. They displaced 110 gallons of gasoline with 2,066 kilowatt hours (kWh) of electricity.
- Each household displaced as little as 1 gallon of gasoline to as much as (almost) 10 gallons during its driving period with 19 kWh to 141 kWh of electricity, respectively.

- On average, for each kWh of electricity they used, these households displaced 0.065 gallons of gasoline (out of the tank).

Recommendations for Further Research

Specific results reported here are less important than the general conclusion that observed behavior deviates from common assumptions regarding important parameters of PHEV design, driving, and charging. At every opportunity going forward, it would seem essential to replace these assumptions with observations. To promote this, every bit of data possible from households driving newly introduced PHEVs and electric vehicles should be analyzed and reported as transparently as possible.

Differences between household access to charging and differences in PHEV designs of the national and California samples may appear small, but given the very large size of both populations from which those samples were drawn, even a few percentage points difference translates into millions of American and hundreds of thousands of California households. This magnitude of scale, combined with the different mixes of electricity sources in different regions of the country and the interaction of these grid mixes and the time-of-day energy and emissions profiles of electricity, speaks to a need for regional analyses of PHEV markets and impacts.

Consumers can be productively engaged in the design of their future. Ongoing research with consumers can continue to guide product and policy design. Consumers' present understandings provide insights into differences between their world views and those of expert groups of researchers, analysts, engineers, and policy makers. Understanding these differences can guide both design and discourse regarding which new products and services are desired, and how and why they are valued. Such understandings are necessary to guide ongoing policy making and market development, and thus an ongoing stream of consumer research would help the State of California adapt policy to the trajectory of changing consumer valuations of PHEVs, as well as consumers' underlying motivations for these valuations.

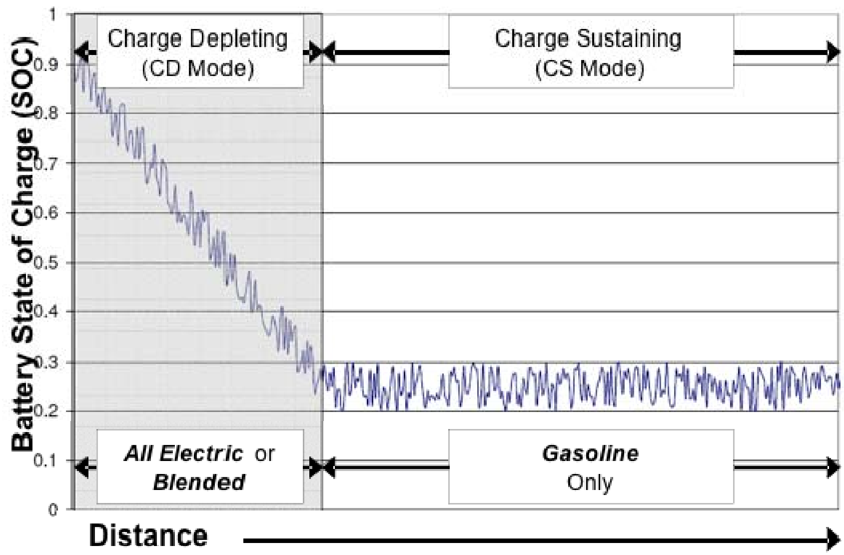
CHAPTER 1:
A Consumer Research Agenda for Plug-In Hybrid Electric Vehicles

Alternative fuel vehicle technologies may play a significant role in helping the U.S. meet goals to reduce petroleum use, air pollution, and greenhouse gas emissions in the transportation sector. Electric drive technologies are receiving renewed attention as potential near-term solutions relative to alternatives such as hydrogen. As hybrid-electric vehicles (HEVs), typified by the Toyota Prius, continue to achieve significant commercial success in the U.S. market, plug-in hybrid vehicles (PHEVs) are touted as the next step in electric drive development (Lemoine et al, 2008).

PHEVs are one step closer to the pure electric vehicle (EV) initially envisioned by California's zero emissions vehicle mandate: users can charge the battery from the electrical grid and drive limited distances (less than 40 miles) in charge-depleting (CD) mode. Figure 1 illustrates CD mode as a reduction in the battery's state of charge, where the vehicle is powered either by electricity only (all-electric operation) or by electricity and gasoline (blended operation). Once the battery is depleted to a minimum state of charge (typically set at a value greater than 0 percent to preserve battery life), the PHEV uses only gasoline in charge sustaining (CS) mode, achieving the fuel efficiency of today's typical HEV. Battery size, degree of hybridization, and drivetrain design can all substantially influence the overall operation of a given PHEV.[1]

[1] For a more detailed discussion of PHEV design concepts, see Axsen et al (2008).

Figure 1: Illustration of Typical PHEV Discharge Cycle



Source: Adapted from Kromer and Heywood (2007, p31). Used with permission from authors

Primary PHEV benefits are straightforward: by supplementing or replacing gasoline combustion with grid electricity consumers could reduce the costs, petroleum use, air pollution and greenhouse gas emissions associated with driving, without the range limitations of pure EVs. Other potential benefits are less obvious: PHEVs could provide mobile energy services, such as backup electricity for home use or storing excess electricity produced by utilities for load balancing (Williams and Kurani, 2006).

The dual fuel potential of PHEVs presents inherent uncertainty to policymakers, automakers, electric utilities, researchers, and other interest groups. Predictions of gasoline and electricity use, as well as the associated emissions, depend on PHEV design, for example, power and energy capacity, as well as driving and charging behavior, for example, location and timing of charge. Due to lack of direct data, previous impact and market analyses have heavily relied on assumptions about such behavior (Winkel et al, 2006; Vyas et al, 2007; Duvall et al, 2007), which are often drawn by proxy from databases of travel patterns and housing stocks. The choice of assumptions can seriously affect results (Lemoine et al 2008) illustrate how varying time of day charge assumptions can substantially influence predictions of electricity grid impacts.

The California Air Resources Board is deliberating how to define a PHEV and assign air emissions credits to automakers for producing them. Similarly, automakers such as Toyota and General Motors are publicly disputing the viabilities of vastly different PHEV designs: one with a smaller battery and relatively low CD range, for example the Prius Plug-in, and one designed to operate as a pure electric vehicle for much longer distances, such as the Volt concept. There is a demonstrated lack of consensus regarding consumer behavior and demand as well as subsequent environmental impacts.

1.1 Are Consumers Impediments to Commercial PHEVs?

Are PHEVs to be encouraged because they represent a rich set of consumer and social values or discouraged as inviting unwelcome, unproductive tradeoffs between the here-to-fore largely separate gasoline and electrical energy systems? One key variable in PHEV commercialization and in the attainment of any environmental and social benefits is the locus of control, that is, who has control over vehicle operations—drivers, vehicle engineers, or regulators?

The fear of regulators, vehicle manufacturers, and energy suppliers is that drivers-in-control could be deleterious to goals for the environment, air quality, energy consumption, energy systems operation, and the ability to warrant vehicles for emissions, fuel consumption, and reliability. In this worldview consumers are seen as at best disinterested and non-compliant, and at worst as anti-compliant. This bias is old and persistent; researchers believe it may be contradicted by a number of real world experiences. Writing a review of consumer energy research nearly three decades ago, McDougall et al (1981) reveal such bias: …recognize that probable energy savings represents a net impact based on potential savings in a technical sense, reduced to allow for imperfect behavioral response. More recently, Friedland et al. (2003) observe the continued absence of people in energy policy: Especially lacking is policy or guidance that incorporates personal choices in energy–use reduction decision-making.

What this pessimistic view of people ignores is that at least some people, if provided with control, information, incentive, and opportunity, as can be provided with a PHEV, will exceed the technical potential possibilities. In interviews with buyers of non-plug-in HEVs, researchers have heard several accounts that suggest their drivers were saving more energy than technical analysts would calculate (Turrentine and Kurani, 2007; Heffner, Kurani, and Turrentine, 2007). This occurred by several means that illustrate the potential effects of driver control, information (feedback), incentive (symbolic and/or financial), and opportunity. In some cases, the HEV prompted further thinking by the owner about energy reductions in other areas of their life. Most directly (and in contradiction to economists' assumptions of a rebound effect, such as, increased driving because of reduced operating costs), some HEV drivers actively attempted to drive their HEV less than the vehicle it displaced. In gaming interviews with non-EV owners, researchers observed that when provided with an incentive in the form of a cost savings through the use of electricity rather than gasoline, these households appeared to quickly learn to adjust their travel between the use of a (hypothetical) FEV and their actual vehicles (Kurani, Turrentine, and Sperling 1994; 1996).

The purpose of the research reported here is to stimulate and report consumer consideration of plug-in hybrid electric vehicles (PHEVs). The primary research reported here is part of the following larger research agenda:

1. Interviews of PHEV pioneers (Funded by the California Institute for Energy Efficiency).
2. Nationwide survey of new car buying household, with representative over-samples of California and cities and towns along the Interstate-80 corridor in northern California. (Funded by the California Energy Commission and reported here.)

3. Household PHEV Demonstration and Market Research. (Funded by the California Air Resources Board, the California Energy Commission and with material and in-kind support of the American Automobile Association Northern California, Nevada and Utah, and Idaho National Laboratory. This research is reported here.)

1.2 Consumer PHEV Demand and Energy Use Field Research

This report covers Task 3.3. The goals of this task were to:

- Assess optimal PHEV design parameters based on consumer demand and energy use patterns for electricity charging and gasoline consumption;
- Stage and assess real world and simulated use of PHEVs.

To achieve these goals, the survey of new car buyers and project were designed to accomplish the following:

1. The PHEV Center's own project supplanted the task of cooperating with other organizations that had PHEV demonstration vehicles. Conversations were held with institutions that either operated PHEVs or planned to do so; these included the U.S. Department of Energy's Idaho National Laboratory (INL), South Coast Air Quality Management District, and others. Ultimately, very few PHEVs were placed in service that would allow consumer research. In the absence of opportunities to study consumers in other demonstrations, the PHEV Center created its own PHEV Demonstration and Market Research project (the project) to allow completion of this contract task.

2. The project's thirteen Prius-conversion PHEVs were instrumented in two stages to collect information such as: mileage, fueling intervals, charging time, energy in/out, and driving information. In the first stage, INL provided an instrumentation package that was standardized across many PHEV demonstration projects. Four instrumentation packages were evaluated. These ranged from off-the-shelf fuel economy instrumentation to purpose-built vehicle instrumentation packages specific to Prius plug-in conversions. In cooperation with INL and Gridpoint, all PHEV conversions in the PHEV Center's demonstration fleet were instrumented with Gridpoint's system. (INL is working with PHEV demonstrations throughout the nation to instrument PHEV conversions with the Gridpoint system.) In stage two, the Center created customized energy feedback devices to make available to drivers an enhanced and integrated, such as, gasoline plus electricity, energy metric. A half-dozen of these additional feedback devices were installed in the PHEVs for a subset of the participants.

3. Assess consumer preference and acceptability for PHEVs, their perceived benefits, desired all-electric range versus vehicle cost, and so on. PHEV designs were solicited from both the national survey sample and the project participants in an on-line questionnaire. The survey sample was representative of households who buy new automobiles in the US and California.

4. Design and conduct a research project on Household PHEV Simulations that will work with drivers of conventional hybrids to assess their preferences for PHEV characteristics through surveys and simulated PHEV operation in their existing vehicles. HEV buyers were included in both the national survey sample and the project participants.

1.2.1 Methods

As stated above, the primary methods to accomplish the purposes and goals of this task were a national survey of new car buyers and PHEV Demonstration and Market Research Project.

The national sample survey was implemented via the Internet. A full explanation of methods and results are presented in Chapter 2. The PHEV Demonstration and Market Research Project provided aftermarket PHEV-conversions (of Toyota's Prius) to households for periods of four to six weeks. During this time, households drove, charged, and refueled the vehicles as if it was replacing one of their own cars. Each household was interviewed three to four times and completed an on-line questionnaire at the beginning and end of their PHEV trial period. Each vehicle reported its driving and energy use, including refueling and charging. Researchers treat this as household data as mediated by the vehicle technology, rather than as vehicle technology data per se. The project participants are tied to the survey sample through the administration of the same PHEV design games to both in the project participants' final on-line questionnaire. A full description of the project and discussion of the results are presented in Chapter 3.

CHAPTER 2: A National Survey to Assess Consumer Valuation of PHEV Designs[2]

Four questions are addressed in this chapter:

1. How aware are U.S. new car buying households of electric-drive vehicles?
2. How many households have regular access to vehicle charging opportunities?
3. What PHEV design(s) currently appeal to consumers?
4. What energy impacts (gasoline and electricity) can researchers anticipate with significant PHEV adoption?

To empirically answer these questions, data were drawn from a web-based survey of new vehicle buying households in the U.S.

Previous electric vehicle constraints analyses estimated that the proportion of households with home charge access to be 28 percent in the U.S. (Nesbitt *et al*, 1992) and 15 to 30 percent in California (Williams and Kurani, 2006). Data for the present study was collected with a 24-hour *Plug-in Potential* diary, improving upon previous research in several ways: (1) instead of creating estimates from census data by proxy researchers elicited charge potential (assessed as the co—location of parking and electricity over which the driver exerted control) directly from respondents, (2) researchers recorded time of day access to allow estimates of daily charge patterns, and (3) researchers limited our focus to U.S. new vehicle buyers, rather than the entire population of U.S. households.

Researchers investigated the design priorities of the potential PHEV market using two design games. Previous research has used stated-preference methods to directly ask survey respondents about purchase intention for a certain PHEV design (Graham *et al*, 2001). Such results are typically unreliable due to the hypothetical and shallow nature of the information provided to respondents. Researchers attempted to overcome this limitation by providing more in-depth information to respondents, described in previous research as a reflexive design (Kurani *et al*, 1996), such as visually depicting the charge potential elicited from the Plug-in Potential diary back to the respondent and providing an informative PHEV buyers' guide. Respondents then completed a PHEV Development Priority game, choosing among several PHEV upgrade possibilities over several iterations, as well as a Purchase Design game, demonstrating interest in a PHEV as purchase intention under different price conditions. In addition to investigating general priority patterns among the sample, researchers also explored two hypotheses gleaned from Kurani *et al*'s (2007) interviews of 23 drivers of PHEV

[2] Material in this chapter was previously published as a UC Davis Institute of Transportation Studies Research Report (Axsen and Kurani, 2008) and is the basis for an article in the Transportation Research Record (Axsen and Kurani, 2009).

conversions: that early PHEV buyers might be particularly interested in (1) all-electric CD operation and (2) attracted to certain levels of high instantaneous fuel economy, such as 100 miles per gallon. Along these lines, researchers also explore the potential market for more aggressive PHEV design proposals, for example GM's Volt concept with 40 miles of all electric range, relative to less aggressive designs, for example Toyota's Plug-in Prius with less than 10 miles of CD range designed primarily for blended operation.

Taken together, the collected information regarding driving patterns, charge potential and design priorities allow the creation of realistic charge scenarios. The potential impacts of battery electric and PHEV charging on electricity generation could be important with widespread adoption (Kurani *et al*, 1997; Lemoine *et al*, 2008; Hadley and Tsvetkova, 2008). Researchers simulate grid impacts under three scenarios to investigate potential tradeoffs between overall gasoline and electricity use and the timing of electricity use.

2.1 Survey Methods

To answer these questions, researchers conducted a web-based survey of 2,373 new vehicle-buying households in the U.S. Relative to mail and telephone methods, the major strength of internet surveys is the high degree of design flexibility. Administrators can interactively adapt questions to previous responses as well as more effectively screen respondents, sequence questions, and avoid item non-response (Rhodes et al, 2003). Internet survey techniques can also enhance response accuracy, particularly for travel diaries (Adler et al, 2002). Lastly, a well-programmed survey will automate data entry to minimize data administration time and cost (Couper, 2000).

However, web-based surveys are susceptible to non-coverage error, where a significant portion of the target population, in this case new car buyers, may be excluded if they don't have internet access. This concern is declining in the U.S. as internet usage rates have grown from 44% in 2000 to over 70% in 2007 (Internet World Stats, 2007). Researchers suspect there is a positive correlation between internet access and likeliness to buy new vehicles, implying an even higher usage rate among our target population. However, non-response bias is still an important concern because those without internet access tend to be more likely to be older, and to have lower income and lower education (Rhodes et al, 2003; Couper et al, 2007).

2.1.1 Questionnaire Design

The survey instrument collected three types of data from new car buyers: 1) their familiarity with electric-drive vehicle technologies, 2) their access to vehicle charge opportunities, such as, electric outlets located at or near their vehicle parking locations, and 3) their plug-in hybrid electric vehicle (PHEV) design priorities. First, awareness was assessed with questions eliciting the stated familiarity of respondents with conventional gasoline, hybrid-electric, electric, and plug-in hybrid electric vehicles. Respondents were then asked to demonstrate their understanding by choosing how each vehicle type could be fueled: with gasoline, electricity through an electrical outlet, or either. The implication of this exercise is not that consumers need to have a deep technological understanding of alternative-drive vehicles to make a purchase.

Researchers feel that a very basic familiarity is required to ensure an understanding of the fundamental benefits of a technology, such as whether or not the vehicle can be plugged in.

Second, charge potential data were collected with a Plug-in Potential diary of driving and parking for a new vehicle (model year 2002 or later) driven several times per week by the respondent's household. Respondents were assigned a day of the week and instructed to record information for a 24-hour period starting with their first trip of the day. Information included the timing and distance of each trip, parking locations, and the proximity of those locations to an electrical outlet. Respondents recorded data in a diary printed from a formatted document and then input the data online using the instrument depicted in Figure 2. An illustration of physical diary is provided in Axsen and Kurani (2008), Appendix A. The respondent's diary day was immediately depicted to them as a graph as seen in Figure 2, using a technique similar to that used by Kurani et al (1994, 1996) to help respondents better understand their own driving behavior and how an electric-drive vehicle could fit into their lifestyle.

Figure 2: Screenshots of Plug-in Potential Diary
(for Hypothetical Respondent)

Plug-In Diary: Wednesday

Trip #:	Location:	Status:	Hours Parked:		2. Electrical Outlet?	3. Distance of Outlet?		
Starting Point	home	Parked	12		Yes			
Trip #:	Destination /Location:	Status:	Start Time:	End Time:	2. Electrical Outlet?	3. Distance of Outlet?	1. Total Distance	2. Highway Distance
Trip #1	work	Driving	08:00 AM	09:00 AM			45	35
		Parked	09:00 AM	05:30 PM	No			
Trip #2	Cindys	Driving	05:30 PM	06:00 PM			10	0
		Parked	06:00 PM	07:30 PM	No			

Details of Trip #3:
(Please fill in all boxes with BLUE outline.)

Trip #:	Destination/ Location:	Vehicle Status:	Start Time:	End Time:	Details	
Trip #3	home	Driving	07:30 PM	08 : 15 PM	2. Total Distance: 30 Miles	3. Highway Distance: 20 Miles
		Parked	08:15 PM	08 : 00 AM	1. Electrical outlet? Yes	2. Distance of outlet? 15 Feet

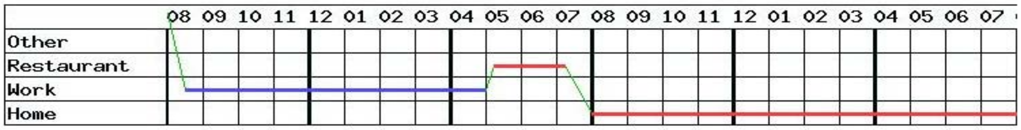
Redo Previous Entry

Is Trip #3 the last trip entry of your Diary Day?

- Yes, this is the last trip entry.
- No, I have at least one more trip to enter.

Submit This Entry as Trip #3

8) To make it easier to understand the diary you just submitted, we've made a visual graph of the parking spots you visited:



Green Line = Driving
Blue Solid Line = Parked with no plug in opportunity
Red Solid Line = Parked with plug in opportunity

Third, PHEV design data were collected in two versions of priority-evaluator games. Commonly, researchers will infer preferences for attributes of alternative fuelled vehicles by presenting respondents with a description of one or several new technologies, followed with a set of hypothetical choice scenarios in which respondents make several choices from sets of vehicles of different attributes (for example, Bunch et al, 1993; Ewing and Sarigollu, 2000; Potogolou and Kanaroglou, 2007). Heffner et al (2007) demonstrate that more in-depth research, such as household interviews, can reveal important information that choice experiments cannot. To improve the quality of data gathered through a nationwide survey, prior to their PHEV design exercises, respondents were provided two types of preparatory information: (1) the 24-hour diary exercise described above served the additional role of reflecting to respondents aspects of their travel patterns and potential access to charge spots, and (2) a PHEV buyers' guide describing basic design options for PHEVs, replicated in full in Axsen and Kurani (2008), Appendix B. Respondents then completed two games, both replicated in Axsen and Kurani (2008), Appendix C. The first was a PHEV Development Priority game in which respondents created PHEV designs over several iterations. Second was a Purchase Design game, similar to the first, but with the design possibilities priced in dollars and respondents could reject buying a PHEV, therefore retaining a conventional vehicle.

One key difference between these games and typical stated choice exercises is that the games are designs, not choices. Rather than choose their most preferred vehicle design from a limited set of options, often repeated several times, specified by the researchers, respondents are presented a design envelope in which they construct their most favored design subject to resource constraints. Kurani et al (1996) discussed the basis for regarding consumer evaluations, especially of novel products such as electric-drive vehicles, as being constructed in the process of choosing (or not choosing).

Both games focused on four PHEV design attributes: (1) hours required for complete charge of a depleted battery, (2) gasoline-only fuel economy in charge-depleting (CD) mode, (3) miles of range in CD mode, and (4) gasoline fuel economy in charge-sustaining (CS) mode. In each game, a base PHEV design is offered with capabilities easily achievable by current battery technology (Axsen et al, 2008): a PHEV that requires up to 8 hours to completely charge, that can be driven for the first 10 miles in CD mode using blended operation that increases fuel economy to 75 mpg, and that can improve fuel efficiency by 10 mpg over a conventional vehicle when operating in CS mode. [3] In both games, respondents were given opportunities to improve each attribute under different resource conditions.

Researchers chose these four attributes due to their importance in shaping PHEV driving, for example, the proportion of miles driven in CD mode, as well as reflecting technological

[3] Note that these PHEV design games are meant to represent designs that are technologically feasible, but not necessarily with exact specifications. For instance, the battery required for our base PHEV design would likely require only 2 to 3 hours to fully charge with a 110 to 120 volt circuit. However, with careful pre-testing, we consciously chose to simplify attribute levels and ignore potential interactions among attributes to create exercises that are more likely to be understood by our respondents than to adhere to experts' knowledge.

capabilities. First, the time to replenish a large depleted battery would take 6-8 hours, but technology exists to allow fast charging in less than one hour—allowing for significantly different charge patterns. Second, currently available PHEV conversions are designed for blended CD operation. Researchers specified upgrades to account for several levels of gasoline only fuel economy in blended operation: 75-100-125 mpg. This range includes the 100 mpg magic number identified as important among some early PHEV conversion owners (Kurani et al, 2007). Automakers such as General Motors have announced plans to release PHEVs designed for all-electric operation. For this reason, researchers included an all-electric upgrade option. Third, CD range depends on battery energy capacity, and proposed designs typically range from 10 miles to 40 miles (Pesaren et al, 2007; Kromer and Heywood, 2007). The fourth category, fuel consumption in charge sustaining (CS) mode, is comparable to the operation of today's hybrid electric vehicles: the battery and electric motor are used primarily to improve the efficiency of the gasoline engine, rather than not to use grid electricity. Most hybridized drivetrains can increase fuel economy by 10 miles to 30 miles per gallon (mpg) relative to a similar size, weight, and performance vehicle.

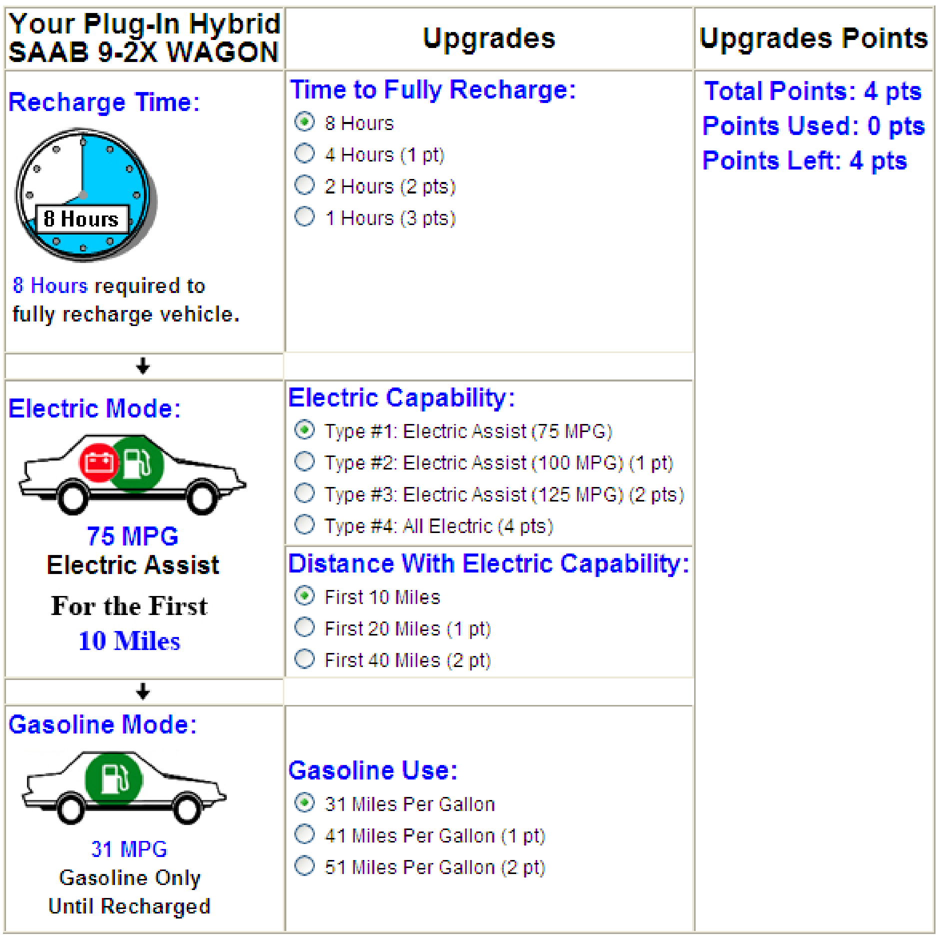
The Development Priority game presented respondents with a hypothetical scenario: the household vehicle for which they kept their Plug-in Potential diary would be upgraded to a PHEV at no cost. The performance and appearance of their vehicle would remain the same, except for the additional capabilities of a plug-in hybrid: a battery that can be plugged in to any electrical outlet to power the vehicle for short distances, as well as a drivetrain that reduces gasoline consumption even after the CD range is exceeded. Respondents were presented with a base PHEV model and given points they must allocate among various potential upgrades. Over five rounds of the Development Priority game, respondents were provided progressively more points (Table 1). For the first three rounds of the game higher levels of upgrades of the four attributes and more combinations of upgrades were also offered, expanding the PHEV design envelope. A screenshot of the game, along with the language used for respondents, is portrayed in Figure 3.

Table 1: Upgrades for PHEV Development Priority Game

Attribute **(base value)**	**Round One:** **(1 point)**	**Round Two:** **(2 points)**	**Rounds Three, Four and Five:** **(4, 6 and 8 points)**
Charge time: (8 hours)	4 hours (1pt)	4 hours (1pt) 2 hours (2pt)	4 hours (1pt) 2 hours (2pt) 1 hour (3pt)
Charge depleting (CD) mpg and type: (75 mpg)	100 mpg (1pt)	100 mpg (1pt) 125 mpg (2pt)	100 mpg (1pt) 125 mpg (2pt) All-electric (4pt)
CD range: (10 miles)	20 miles (1pt)	20 miles (1pt) 40 miles (2pt)	20 miles (1pt) 40 miles (2pt)

Charge sustaining (CS) mpg: (Current mpg* +10)	Current mpg +20 (1pt)	Current mpg +20 (1pt) Current mpg +30 (2pt)	Current mpg +20 (1pt) Current mpg +30 (2pt)

Figure 3: Screenshot of Development Priority Game (Round Four)



The Purchase Design game framed the PHEV design exercise in the context of a future vehicle purchase. The questionnaire first elicited information about the anticipated price, make, and model of the next new vehicle the respondent's household would likely buy. The respondent then completed two PHEV purchase exercises, each comparing their anticipated conventional vehicle with a PHEV version of the same. Respondents were presented with a high price and low price PHEV purchase conditions, where prices in both conditions also depended on whether the vehicle was a car or truck, Table 2. As in the Development Priority game, each exercise started with the same base PHEV model, with additional upgrades available for added price. In each exercise, the respondent could choose either their anticipated conventional vehicle, the offered base PHEV, or to upgrade the PHEV. Figure 4 portrays a screenshot of this exercise.

Because battery and drivetrain costs are highly uncertain, upgrade prices in Table 2 are largely hypothetical. That is, researchers are less concerned with whether the prices researchers now present to respondents will be right in a future, if and when PHEVs are marketed, and more concerned with how respondents pick and choose from different energy sources, energy efficiencies, and distinct operating modes within different price contexts. The price contexts researchers present are not wholly imaginary. Overall prices are based on short term (high price) and long term (low price) estimates from previous studies: Markel (2006) estimates incremental costs for PHEVs with all-electric capabilities (7 to 19 kWh) at $6,000 to $22,000, while Kalhammer et al (2007) provide cost estimates for PHEVs with slightly lower capacity batteries (4 to 14 kWh) in the range of $2,000 to $8,000. For comparison, PHEV designs in our survey ranged from $3,000 to $13,500 for cars in the high price condition, and from $2,000 to $7,250 in the low price condition. For trucks, base model prices are increased and upgrades doubled based on Duvall et al's (2002) estimates of a full size SUV PHEV requiring 75 percent more energy capacity and 190 percent more battery power to achieve the same CD performance as a compact car PHEV.

Figure 4: Screenshot of Purchase Design Game
(High Price, Vehicle Model Customized for Respondent)

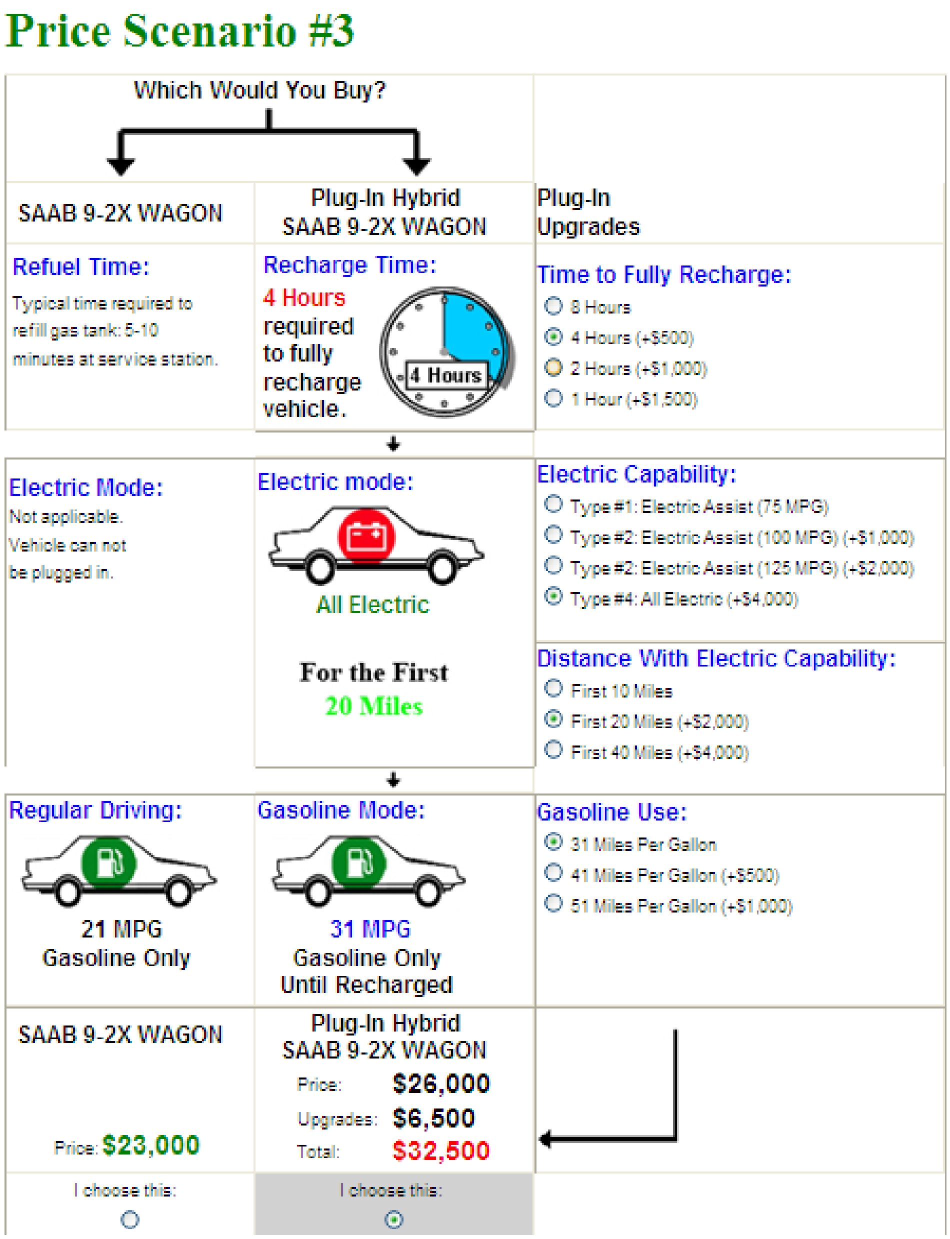


Table 2: Price of Upgrades for Purchase Design Game

Attributes (base level)	Attribute level	High price Car	High price Truck	Low price Car	Low price Truck
Base premium		$3,000	$4,000	$2,000	$3,000
Charge time (8 hours)	4 hours	+$500	+$1,000	+$250	+$500
	2 hours	+$1,000	+$2,000	+$500	+$1,000
	1 hour	+$1,500	+$3,000	+$750	+$1,500
CD mpg and type (75 mpg)	100 mpg	+$1,000	+$2,000	+$500	+$1,000
	125 mpg	+$2,000	+$4,000	+$1,000	+$2,000
	All-electric	+$4,000	+$8,000	+$2,000	+$4,000
CD range (10 miles)	20 miles	+$2,000	+$4,000	+$1,000	+$2,000
	40 miles	+$4,000	+$8,000	+$2,000	+$4,000
CS mpg (Current mpg +10)	Current mpg +20	+$500	+$1,000	+$250	+$500
	Current mpg +30	+$1,000	+$2,000	+$500	+$1,000

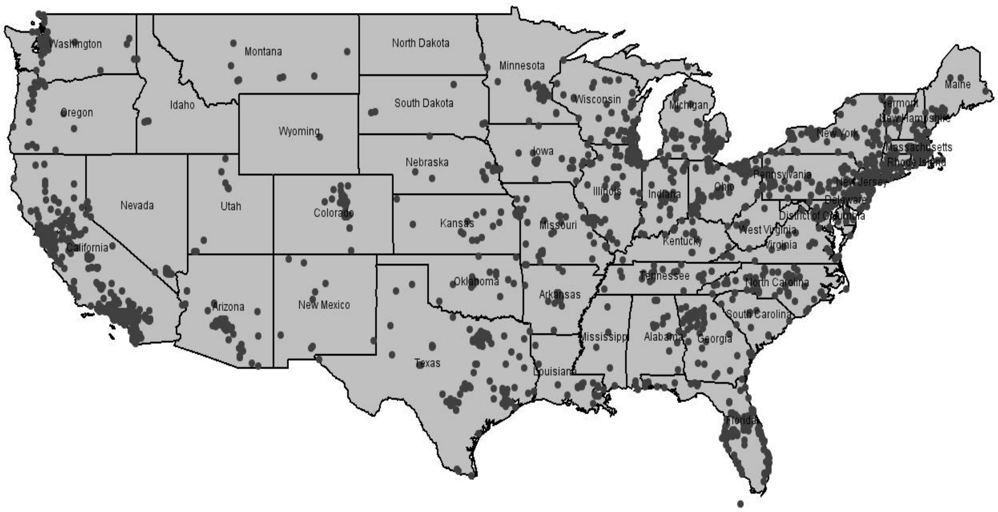
2.1.2 Sample Construction

Our target population is new vehicle buying households in the U.S. To qualify, respondents had to own a new gasoline vehicle that they purchased in 2002 or later, which they personally drove at least 3 times per week. The respondent also must have played a significant role in the household's decision to purchase this vehicle. In limiting our study to this population, researchers imply that the early market for PHEVs is limited to households that tend to buy new vehicles in general. In total, 2,664 respondents completed the entire survey in December of 2007.Researchers removed 291 respondents with incomplete diary data, leaving 2,373 used in this study.

Figure 5 portrays the geographic distribution of the sample, which corresponds to population density. Two regions, California and a particular area in Northern California, were intentionally oversampled to permit separate analyses. Because the present study focuses on the overall U.S. vehicle market, all data has been weighted to be representative of the whole U.S. including California.

Harris Interactive recruited respondents for this survey from their internet panel. To counteract concerns of non-coverage and non-response error, Harris estimates weights to better match the realized sample to the target population. Weights are based on geographic, demographic and attitudinal data, and matched to existing databases collected through multiple survey modes (including mail and telephone). All results presented in this study use these weights to match our sample to the U.S. population of new vehicle buyers.

Figure 5: Geographic Distribution of PHEV Sample Across the United States (Alaska Not Shown)



To assess the external validity of our sample, as well as the impact of Harris' weights, researchers compare sample distributions according to five socio-demographic variables in Table 3: respondent gender, education and age, and household income and housing type. General population estimates are from the 2000 Census, as well as the Current Population Survey (CPS) and the American Household Survey (AHS). However, because our target population (new vehicle buyers) is likely to be of higher socioeconomic status than the general population, researchers also drew a sub-sample of over 10,000 households owning new vehicles from the 2001 National Household Travel Survey (NHTS). Comparing our weighted sample to the NHTS, researchers find that the income levels of both samples are about 42 percent higher than general population estimates from similar years (2007 and 2000 respectively). Also, gender, age, and housing type follow similar distributions between the two samples of new vehicle buying households. Education levels are slightly higher in the present study, with 56 percent having a college degree of higher compared to 48 percent in the NHTS sample. Table 3 also shows that applying the Harris weights has little effect on gender, income, and housing type, but does influence education and age distributions in the same directions as the NHTS sample. Researchers conclude that the sample matches well with other samples of new car owners on these socio-demographic measures, strengthening claims that results can be extended to the population of new-car owning, and therefore new car-buying, households.

Table 3: Comparing Demographic Distributions of Present and Previous Samples

	Target	New vehicle buyers			General population	
	Year	2007	2007	2001	2007	2000
	Survey Type	PHEV unweighted[a]	PHEV weighted[b]	NHTS[c]		
	Sample size	2,373	2,373	10,188		
					Pop. Est.[g]	Census [h]
Gender[d]	Male	49.3%	52.2%	43.5%	49.3%	49.1%
	Female	50.7%	47.8%	56.5%	50.7%	50.9%
					CPS[i]	Census [h]
Education[d]	High school or lower	9.3%	19.4%	31.2%	46.6%	48.2%
	Some college	25.3%	24.7%	20.7%	19.0%	21.0%
	College degree	38.0%	36.7%	32.8%	25.7%	21.9%
	Graduate degree	27.4%	19.2%	15.2%	8.7%	8.9%
					Pop. Est.[g]	Census[h]
Age[d]	15 to 24	2.5%	3.3%	4.5%	17.7%	17.8%
	25 to 34	12.6%	17.8%	16.2%	16.9%	18.0%
	35 to 44	18.2%	21.7%	22.8%	17.9%	20.4%
	45 to 54	25.9%	24.3%	25.5%	18.2%	17.1%
	55 to 64	26.2%	21.6%	15.7%	13.6%	11.0%
	>64	14.6%	11.3%	15.4%	15.7%	15.8%
					CPS[i]	Census[h]
Income[e]	< 30 k	5.5%	6.3%	12.2%	31.0%	35.1%
	30 k to 60 k	28.2%	26.0%	32.7%	28.6%	31.9%
	> 60k to 100k	33.7%	32.5%	32.4%	21.3%	20.7%
	> 100k	32.7%	35.3%	22.7%	19.1%	12.3%
	Mean income[f]	$86,243	$87,911	$ 72,478	$61,870	$50,864
	Ratio of new vehicle buyer mean income to general population mean income	1.39	1.42	1.42		
					AHS[j]	AHS[j]
Housing type[e]	Detached house	78.4%	78.0%	80.7%	64.3%	62.8%
	Attached house	8.9%	8.3%	7.6%	5.7%	6.8%
	Apartment	9.5%	10.2%	8.9%	23.7%	23.9%
	Mobile home	3.1%	3.5%	2.8%	6.4%	6.6%

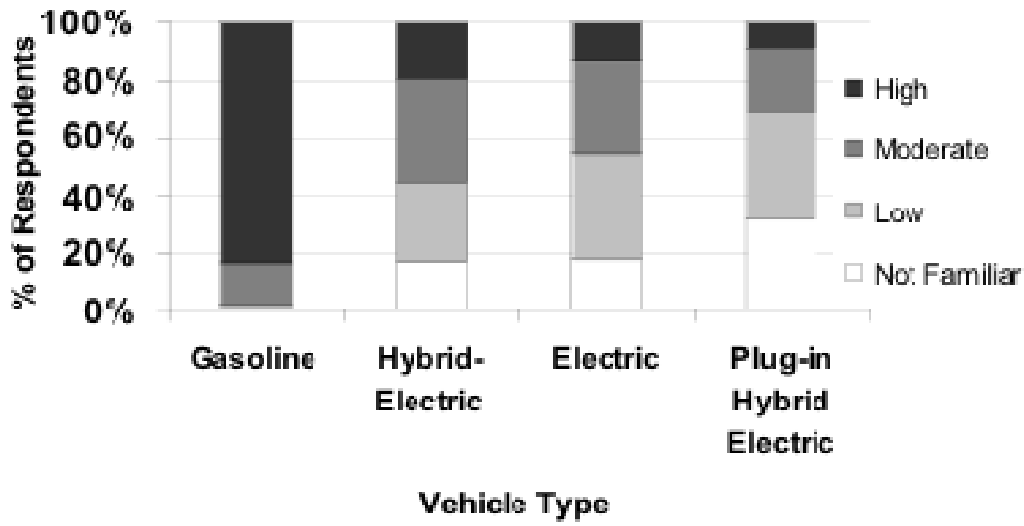
[a] Without Harris Interactive's weights; data only weighted to correct for California over-sample.
[b] Data used for this study: using U.S. weights provided by Harris Interactive.
[c] NHTS sample limited to responding households that had purchased a vehicle of model year 2001 or 2002.
[d] Data reported for respondent only.
[e] Data reported for respondent's household.
[f] Mean approximated from the product of middle values assigned to each income category and the proportion of the sample in that category.
[g] 2007 Annual estimates of the population by the Population Division of the U.S. Census Bureau.
[h] 2000 Census by the U.S. Census Bureau.
[i] 2007 Current Population Survey by the U.S. Census Bureau.
[j] 2005 and 1999 American Household Surveys by the U.S. Department of Housing and Urban Development.

2.2 National Survey Results

2.2.1 New Car Buyers' Awareness of Electric-Drive Vehicles

Among respondents, stated familiarity with vehicle technologies corresponded to real-world experience with automobiles; high levels of familiarity were most common for conventional gasoline vehicles, followed by HEVs, EVs, and PHEVs, Figure 6. Familiarity with PHEVs was lowest: 69 percent of respondents reported low or no familiarity. A question eliciting demonstrated understanding of motor vehicles indicates that the vast majority of respondents understood that conventional gasoline vehicles could only use gasoline, while electric vehicles can only use electricity, Figure 7. But things are a good deal less clear for HEVs and PHEVs: 25 percent of respondents thought that a PHEV could only use electricity and 68 percent of respondents thought that an HEV could be refueled either with gasoline or by plugging in to an electric outlet. The latter is clearly false for the most common expert definitions of an HEV. This last point demonstrates enormous potential for misunderstanding PHEVs among new vehicle buyers, the majority of which seem to think that currently available hybrids can, or must, be plugged in to the electricity grid. An alternative explanation is that choice of wording (hybrid-electric) may have been too formal relative to common usage of the word hybrid. In either case, there is at least widespread confusion regarding electric-drive terminology, and perhaps widespread misunderstanding of the functions, requirements, and benefits of different electric-drive technologies.

Figure 6: Stated Familiarity With Electric-Drive Vehicles (All Respondents)



2.2.2 Charge Access

Results from the Plug-in Potential vehicle diary indicate that more new vehicle buyers may be pre-adapted for vehicle charging than previously estimated, Figure 8. Following Graham *et al* (2001), researchers consider a parking spot to be viable for charging if located within 25 feet of an electrical outlet. Of the 2,373 respondents, 59.5 percent found at least one viable charge location during their 24-hour diary day, and 52.4 percent identified one at their home. For the remainder of this study, researchers consider these 52.4 percent of the sample to represent the higher home charge potential segment among new vehicle buying households. That is, respondents who identified an electrical outlet within 25 feet of their vehicle parking spot at their home location at some time during their 24-hour diary.

Fewer respondents found non-home charge locations: 4.8 percent found outlets at work (6.3 percent of employed respondents), 5.4 percent at the home of a friend or family member, 2.3 percent at a store or restaurant, and 9.7 percent at all other locations. Figure 8 also depicts the sensitivity of estimated charge access to the assumption of the maximum distance of the electrical outlet from the vehicle. Home charge access ranges from as high as 60.7 percent if researchers allow 50 feet between the parked vehicle and the nearest electrical outlet, to a low 35.8 percent if the outlet must be within 10 feet of the vehicle.

Figure 7: Demonstrated Understanding of How to Fuel an Electric-Drive Vehicle (All Respondents)

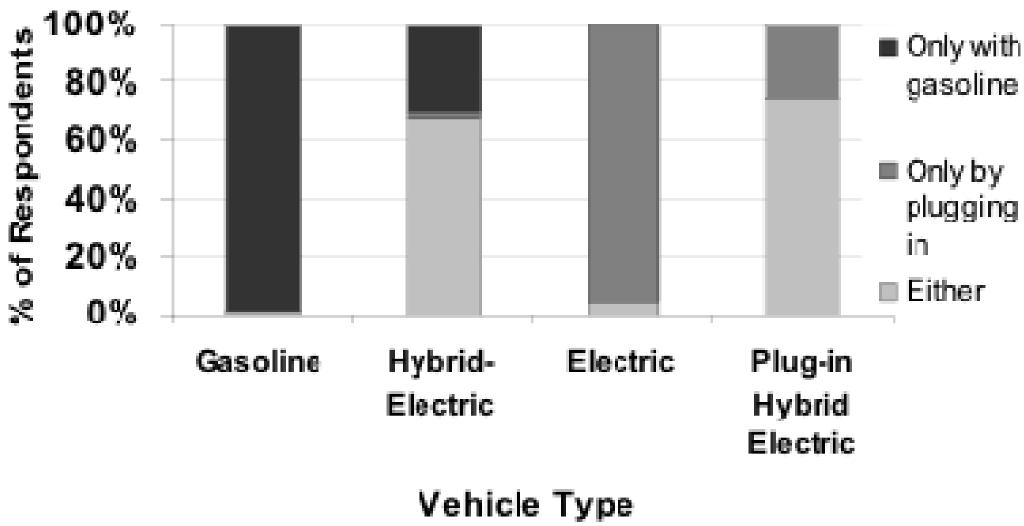


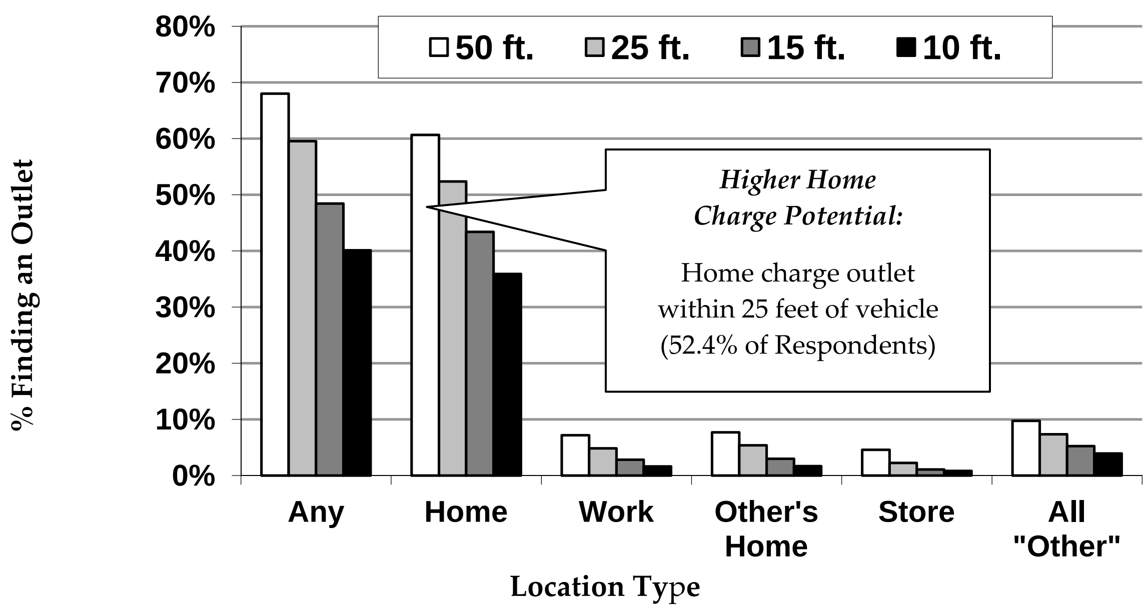
Figure 9 depicts the split of this higher home charge potential segment by housing type: detached homes (single family dwellings), attached homes (including duplexes and townhouses), apartments, and mobile homes. Most respondents lived in detached homes (single family dwellings), and most respondents who lived in detached homes parked their vehicle at home within 25 feet of an electrical outlet. Over the entire sample, 45.9 percent of new car buyers live in a detached home and park near an outlet. Somewhat less than half of residents of attached homes and mobile homes park a car at home near an outlet. Only about one-in-six apartment dwellers parks a vehicle near an outlet. Overall, residence in a detached home is positively correlated with at-home charge potential, but is neither necessary nor sufficient.

Figure 10 shows that the proportion of the sample with higher home charge potential is highest for those parking in attached garages (71.9 percent) and detached garages (61.6 percent).

Driveway and carport locations yield lower proportions of 42.4 and 40.3 percent, respectively. The lowest proportions were found for respondents parking on the street (17.4 percent) and in parking lots (4.7 percent). Findings suggest that the use of home garages supports at-home charge potential, but this condition is neither necessary nor sufficient.

Researchers also investigated driving and charge potential over a 24-hour cycle (in 15 minute intervals); the sample was proportionally assigned a weekday, Figure 11, or weekend-day, Figure 12 on which to complete their diary. On weekdays, the proportion of respondents who were driving at any point in time follows an expected daily pattern, peaking during common commute hours at 7:30am and 5:00pm. At a given point in time, total charge potential ranges from over 50 percent of respondents from 9:00pm to 7:00am, to under 20 percent from 10:00am to 3:00pm. Throughout the day, home is by far the most frequent location of charge opportunities within respondents' existing travel and charge potential. Neither work nor other non-home locations have charge potentials that surpass home for percent of respondents for any 15 minute interval during the day. The general pattern in Figure 11 is consistent with driving patterns. Charge potential drops when many respondents are driving or parked at work or other locations, and rises when vehicles are parked at home.

Figure 8: Access to Charge Spot by Location and Outlet Distance (All Respondents, n = 2,373)



As seen in Figure 12, relative to weekdays, driving patterns on weekend days do not have the two morning and afternoon peaks, but rather a single broad mid-day rise to a peak at 12:30pm, with a lesser peak in the later evening. Weekend charge potential during any given 15 minute interval ranges from a high of 50.3 percent to a low of 28.6 percent of all respondents; home also dominates the potential charge locations.

2.2.3 PHEV Design and Value

Researchers used charge potential estimates from the previous section to shape the analysis of respondents' PHEV design games. Researchers divided the sample into three segments according to their demonstrated charge potential:

1. Higher Home Charge Potential: this segment consists of the 52.4 percent of respondents that found an at-home electrical outlet within 25 feet of their vehicle during their diary day, Figure 8.
2. Lesser Charge Potential: this segment includes the 23.7 percent of respondents that did not identify a home charging location in their diary day as specified above, but elsewhere in the survey indicated they could potentially charge at one or more locations at least 8 hours over an average week.
3. No Charge Potential: the remaining segment, 23.9 percent, includes all respondents that did not indicate they could potentially charge their vehicle at one or more locations for at least 8 hours in an average week.

Figure 9: Access to Home Charge by Housing Type
(All Respondents, n = 2,373)

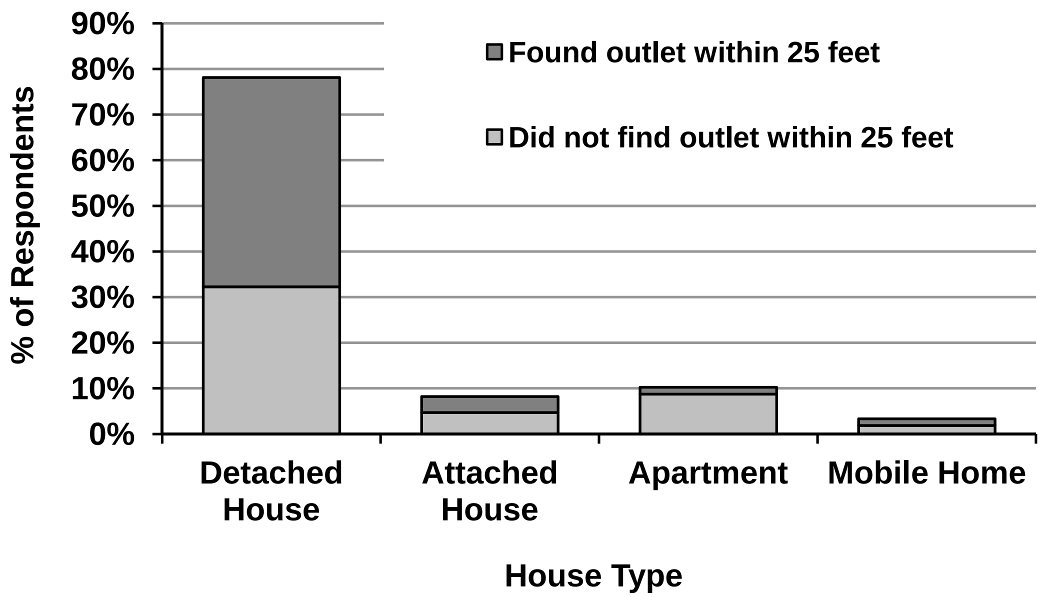


Figure 10: Access to Home Charge by Type of Home Parking
(All Respondents, n = 2,373)

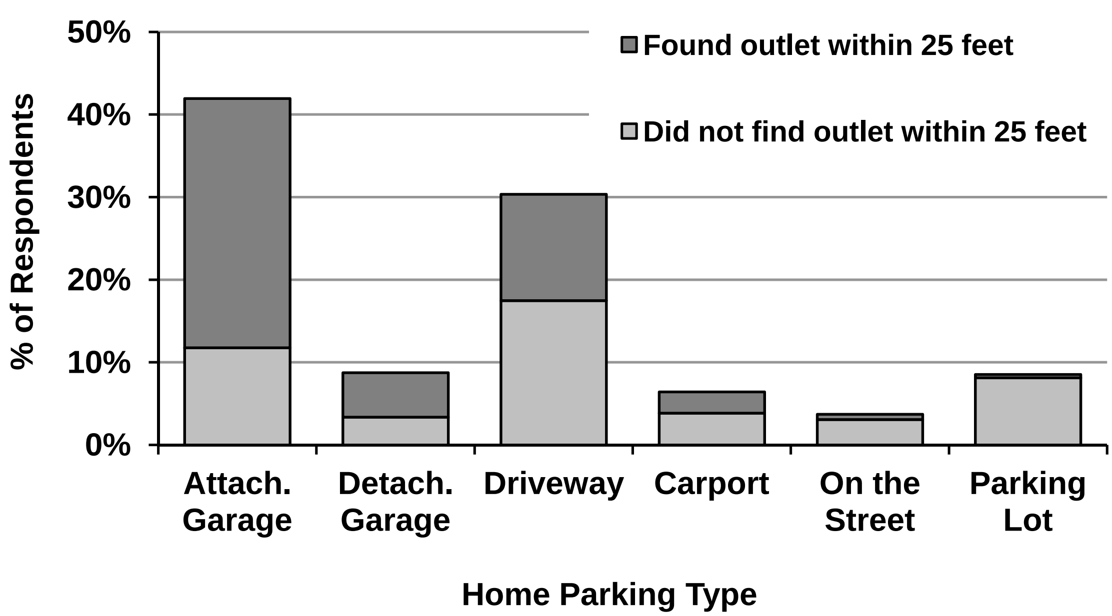


Figure 11: Time of Day Driving and Charge Potential
(Weekdays Only, n = 1,650)

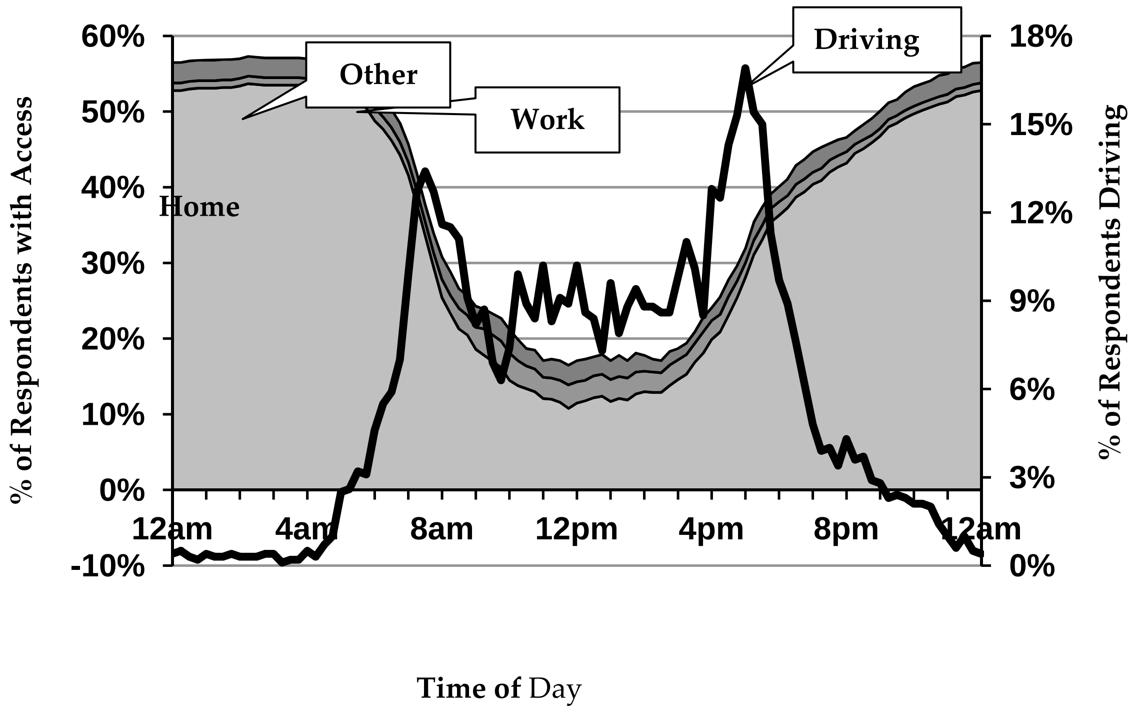
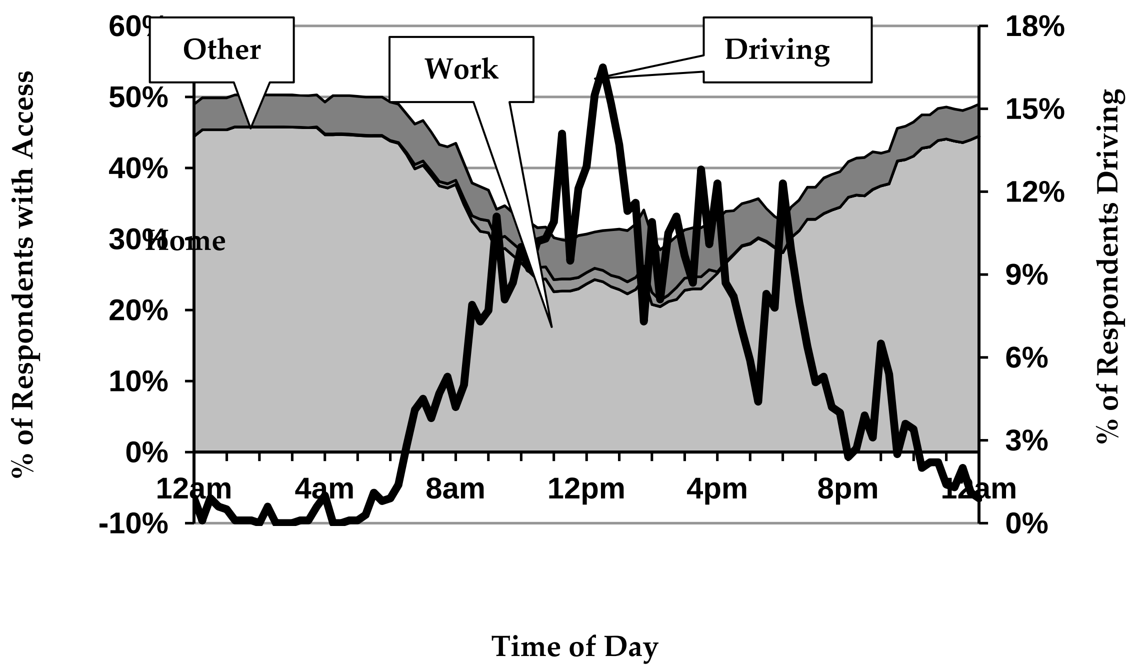


Figure 12: Time of Day Driving and Charge Potential
(Weekend Days Only, n = 493)



Within each charge segment, researchers compared interest in PHEVs as measured by whether the respondent stayed with a conventional vehicle or designed a PHEV to be their next new vehicle in the Purchase Design games described in Section 2.1 (Figure 13). Among respondents with higher home charge potential, 64.1 percent designed a PHEV for their next new vehicle in the high price condition. Such purchases of PHEVs are more frequent across all charge potential segments in the low price condition than in the high price condition, by 11 to 16 percentage points. PHEV purchase intentions are less frequent in segments with less demonstrated charge potential, such as, the lesser and no charge potential segments. Surprisingly, this decrease is only slight; relative to the higher home charge potential segment, purchase intention decreases by 3 percentage points for the lesser charge potential segment, and by 12 to 17 percentage points for the no charge potential segment. Regardless of the degree of demonstrated charge potential, the majority of respondents in each segment assigned significant value to a vehicle with plug-in capabilities they designed.

Because charge opportunities are relatively sparse at work and other non-home locations, researchers isolate home charging as the key criteria to characterize a potential early PHEV market in this analysis. This constraint is substantiated by the experience of drivers of PHEV-conversions reported by Kurani et al (2007). Researchers feel that the higher home charge potential segment identified above provides a conservative yet realistic sub-sample from which to explore the size of early PHEV markets; researchers limit further consideration of the early PHEV market to the higher home charge potential segment. Researchers further constrain this segment based on PHEV interest as indicated by purchase intentions in the high price condition. Thus, researchers select the 33.5 percent of respondents that demonstrate both access to sufficient charge infrastructure and PHEV interest as a group best representing the early PHEV market. Researchers will refer to this subset as the potential early market respondents.

Focusing on the interests of these potential early market respondents, results of the two PHEV design games are summarized in Figure 14. PHEV performance priorities varied substantially; no single PHEV design emerged as a favorite of the majority. In Round One of the Development Priority game, respondents were given one point to allocate towards one upgrade to the base PHEV model. As described in Chapter 2, four upgrades were available in the first round: charge time (from 8 to 4 hours), gasoline-fuel economy during CD operation (from 75mpg to 100 mpg), CD distance (from 10miles to 20 miles), or CS gasoline-fuel economy (from 10mpg to 20 mpg over the conventional version of the vehicle). Improving the CS gasoline-fuel economy was the most frequently chosen upgrade (41.1 percent). [4] The general ranking of attribute upgrades in Round One continues through later rounds: a higher percentage of potential early market respondents designed PHEVs with CS mpg upgrades than faster charge times.

All-electric operation in CD mode was first offered to respondents in Round Three. Only 3.4 percent made this upgrade, which came at the expense of any other upgrades available in prior rounds. In Round Four, the proportion of potential early market respondents designing a

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[4] Although the percentages add up to 100 across the columns in Round One, they do not in further Rounds because respondents have enough points to choose multiple upgrades.

PHEVwith all-electric operation rose to 12.3 percent. Figure 15 portrays the 23 different possible PHEV designs possible in Round Four. This is the first round providing a design envelope allowing respondents to choose a PHEV with 40 miles of all-electric range, a vehicle similar to GM's Volt concept. Only 4.7 percent of potential early market respondents chose this specific design. Overall, all-electric operation, a feature stated by some automakers to be essential to assure market success, was not chosen frequently when points were relatively scarce, such as in Rounds Three and Four.

Figure 13: PHEV Interest Among Three Charge Segments
(All Respondents, n = 2,373)

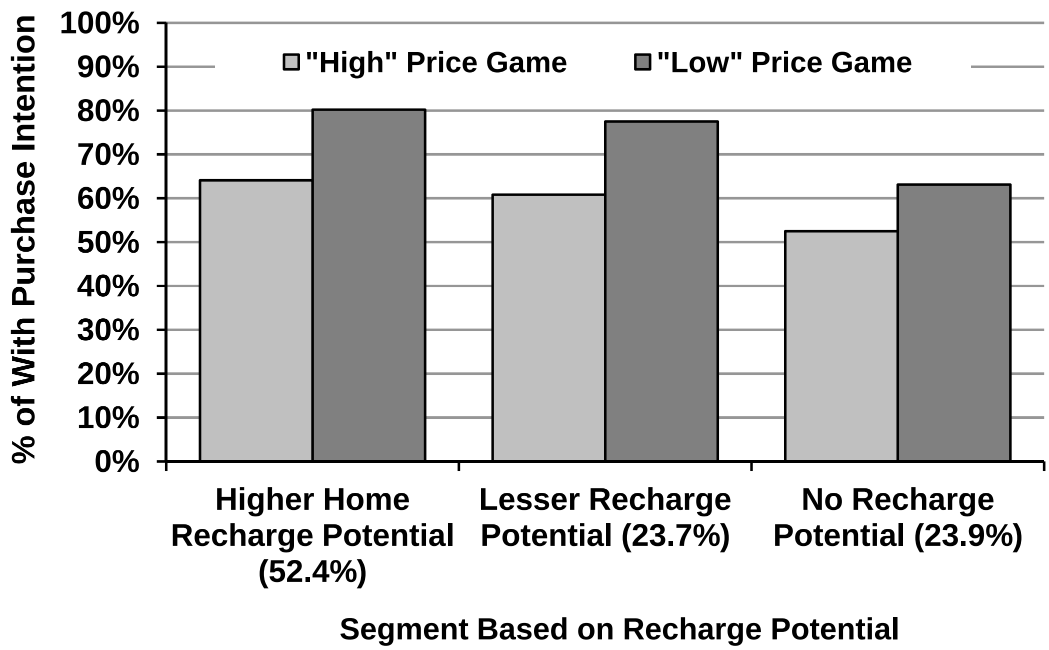
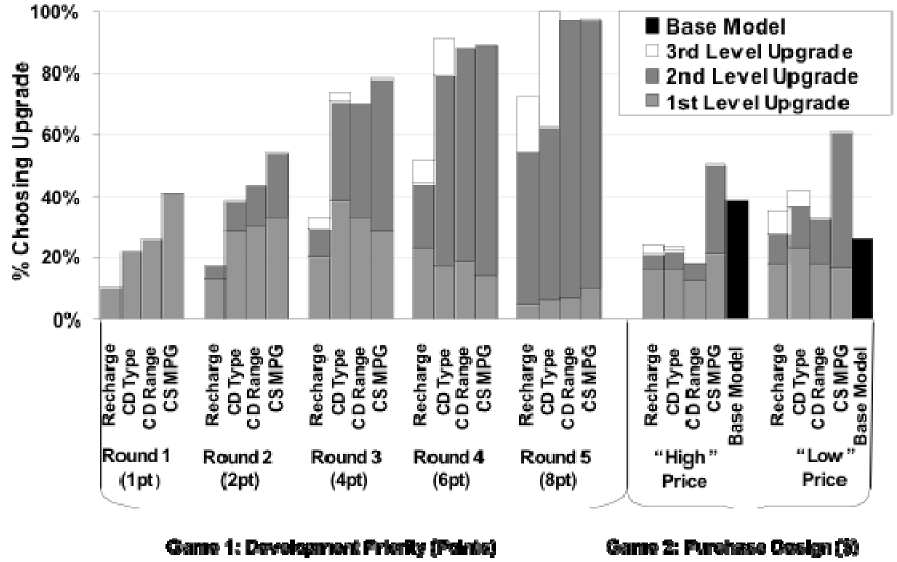
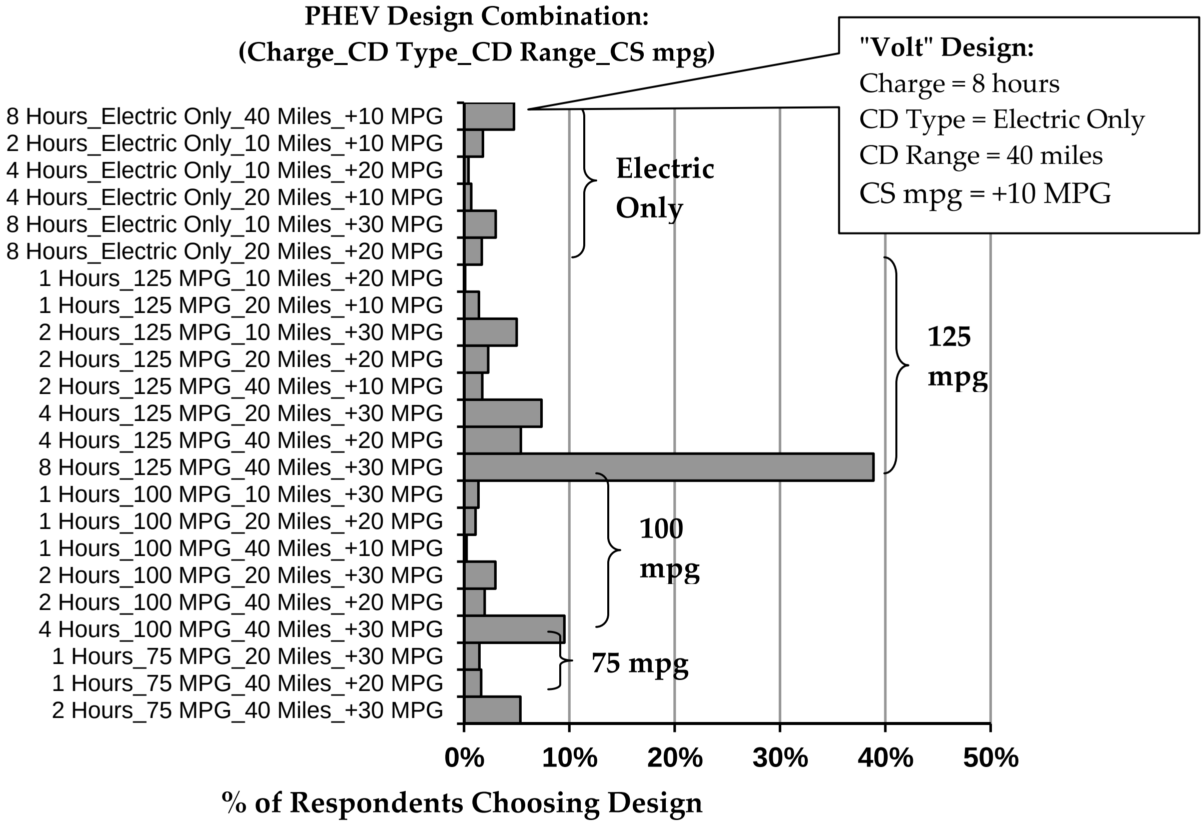


Figure 14: Attribute Selection in Both Design Games
(Early Market Potential Respondents Only, n = 827)



As previously noted, results of the Purchase Design game suggest that the majority of higher home charge respondents (64.1 percent to 80.2 percent) would value PHEV capabilities in their next vehicle. Figure 14 depicts the proportion of upgrades chosen in the price conditions detailed in Table 2. A substantial portion of potential early market respondents chose the proffered base PHEV model, 38.8 percent in the high price condition, and 26.5 percent in the low price condition. Among those to upgrade, overall patterns are similar to the Development Priority game; CS fuel economy upgrades were incorporated into the PHEV more often than other upgrades, and there is no evidence of the strong interest in all-electric operation observed among some pioneer PHEV conversion drivers (Kurani et al, 2007). All-electric upgrades were chosen by 1.5 percent and 5.7 percent of respondents in the high and low cost conditions, respectively. However, unlike the tradeoff game, CD operation and range improvements were chosen relatively less often, likely due to the representation of the added price of increasing battery power and energy density.

Figure 15: Distribution of Selected PHEV Designs in Round Four of Development Priority Game (Early Market Potential Respondents Only, n = 827)



2.2.4 PHEV Energy Use Scenarios

To create scenarios of gasoline and electricity use among plausible early PHEV buyers, researchers integrate the information presented thus far from respondents in the higher home charge potential segment: driving behavior and charge potential as recorded by their 24-hour diary, and PHEV design choices as demonstrated in the Purchase Design game. In other words, researchers create scenarios of gasoline use and charge patterns for each potential early market respondent as if they were driving their chosen PHEV design on their 24-hour vehicle diary day. These scenarios rely on the following assumptions:

- Gasoline use is modeled using the estimated miles per gallon (mpg) of the vehicle, without accounting for potential variation in driving patterns. In other words, if the vehicle is rated at 50 mpg, researchers assumed this constant rate for each mile driven, neglecting the potential for different drive patterns over a given trip or across drivers.

- For charge depleting (CD) operation, electricity use (kWh/mile) and available battery energy capacity (kWh) is estimated as in Table 4, based on car estimates from Kromer and Heywood (2007), scaled up to truck estimates based on Duvall et al (2002).

- Each vehicle's assumed battery state of charge at the beginning of the day is a function of the distance driven the previous day, assumed to be the same as the diary day due to lack of multi-day data, and the respondent's estimated hours of charge potential from the previous day, elicited elsewhere on the survey.
- Following Lemoine et al's (2008) assumptions, the minimum charge rate for a PHEV battery using a regular 110-120 V outlet is 1 kWh per hour. If the respondent's chosen PHEV design has a charge rate higher than that required for their battery size, researchers apply the faster of the two charge times. For example, if the respondent chose a PHEV requiring 8 hours for complete charge, yet their battery size is only 1.9 kWh, requiring a maximum of 1.9 hours for full charge, the researchers applied the 1.9 hour time. In contrast, if the same respondent selected a charge time of one hour, researchers applied the one hour time.
- Following Lemoine et al's (2008) assumptions, vehicle charging is approximately 83 percent efficient; increasing the battery's state of charge by 1 kWh requires 1.2 kWh from the electrical outlet.
- Each scenario is scaled up to represent 1 million vehicles. This value is not selected in anticipation of a particular sales volume for a particular year, but instead is a relatively feasible market size that serves to normalize energy use to allow comparisons across scenarios (with different sample sizes)[5].
- Vehicles are charged on a daily basis as detailed in the scenario descriptions below.
- The PHEVs are used precisely as were their non-PHEV variants; the scenarios are based on replicating the travel-days as recorded in the diaries and do not allow for households to change the assignment of vehicles within the household or otherwise change vehicle use in response to the PHEV.
- Researchers assume for this analysis that one day cross-sectional data are adequate to characterize travel and therefore energy impacts. One day diaries systematically under-represent longer travel unless the sampling is conducted according to the frequency distribution of travel-day or trip distances across people and days. By sampling across all seven days of the week researchers attempt to reduce the effect on the analysis, but do not represent that it is immune. It seems plausible that we, and anyone using one day travel data, will underestimate total energy use and gasoline use in particular. Researchers leave the estimation of the size of this potential problem to future research.

Following these assumptions, researchers created four scenarios using data from the 827 Potential Early Market respondents:

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[5] An alternative approach would be to estimate the effect of each charge scenario on the size of the potential PHEV market, such as the addition of potential PHEV buyers resulting from the expansion of public vehicle charge infrastructure, for example at the workplace. However, we leave such analyses to future research, and instead focus on a set market size for each scenario.

1. No PHEVs In this scenario, researchers estimate and aggregate the gasoline used by the respondents on their actual diary days.

2. Plug and Play In this scenario, researchers simulate the gasoline used for driving and the electricity used for charging, allowing that the conventional vehicles are displaced by a vehicle with the PHEV upgrades chosen in the high or low price conditions of the Purchase Design game. Drivers are assumed to charge whenever they are parked within 25 feet of an electrical outlet. In other words, there are no pricing mechanisms, for example, time of use electricity tariffs, or technologies, for example, smart charging mechanisms, to divert charging to off-peak.

3. Enhanced Worker Charging Access This scenario starts with the conditions in Plug and Play, but further supposes that all workers can charge a vehicle at work.

4. Off-Peak Only Charging Finally, using the same charge potential and PHEV designs as Plug and Play, in this scenario no PHEV charging is allowed during daytime peak hours, 6am to 8pm. Smart charging technology is used to optimize the timing of electricity use over this period, represented as a flat line. The actual shape of this line would likely vary according to the needs of a particular electric utility.

Table 4: Assumed PHEV Specifications

CD mpg		Car	Truck
75 mpg	CD electricity use	0.19 kWh/mile	0.32 kWh/mile
	10 mile capacity	1.9 kWh	3.2 kWh
	20 mile capacity	3.8 kWh	6.4 kWh
	40 mile capacity	7.6 kWh	12.8 kWh
100 mpg	CD electricity use	0.20 kWh/mile	0.34 kWh/mile
	10 mile capacity	2.0 kWh	3.4 kWh
	20 mile capacity	4.0 kWh	6.8 kWh
	40 mile capacity	8.0 kWh	13.6 kWh
125 mpg	CD electricity use	0.21 kWh/mile	0.36 kWh/mile
	10 mile capacity	2.1 kWh	3.6 kWh
	20 mile capacity	4.2 kWh	7.2 kWh
	40 mile capacity	8.4 kWh	14.4 kWh
All electric	CD electricity use	0.26 kWh/mile	0.45 kWh/mile
	10 mile capacity	2.6 kWh	4.5 kWh
	20 mile capacity	5.2 kWh	9.0 kWh
	40 mile capacity	10.4 kWh	18.0 kWh

Taken together, these scenarios are meant to represent potential boundary conditions, that is, where the entire market adheres to a selected condition (no regulation, enhanced workplace policy, or off-peak charging). The early PHEV market may include elements of more than one of these scenarios, as well as other potential conditions researchers do not consider here, all of which are likely to change over time. However, the purpose of this exercise is to present these boundary conditions to frame discussions of the potential benefits and drawbacks of different charge strategies and policies.

Figure 16 to Figure 19 portrays each scenario for respondents who completed weekday diaries given the PHEV designs they selected in the high price conditions. Results from respondents with weekend day diaries, as well as low price conditions PHEV designs, are detailed in Table 5. Each figure depicts the time of day gasoline use in gallons per minute and electricity use (MW) per million vehicles over a 24-hour period. The area under each curve represents the total gallons of gasoline, or MWh of electricity, used over the day, respectively. In the Plug and Play scenario, most charging occurs at home locations, peaking at 6:00pm at 596 MW (705 MW in the low price condition)—significantly lower than the 1,200 MW peak anticipated by Lemoine et al (2008) for 1 million PHEVs. Their higher peak electricity demand estimate is due to their assumptions about a uniform PHEV design across the market, 20 miles of all-electric CD range, and relatively uniform charging patterns of PHEV drivers.[6] In contrast, the present study allows for substantial variation in PHEV designs and daily driving.

[6] In each charge scenario presented by Lemoine et al (2008), PHEV drivers are assumed to begin charging at approximately the same time of day for the same duration.

Table 5: Summary of Charge Scenarios, Scaled to One Million PHEVs (Early Market Potential Respondents Only, n = 827)

Scenario		PHEV Design Game 2: High price		PHEV Design Game 2: Low price	
		Weekday (n = 590)	Weekend (n = 168)	Weekday (n = 590)	Weekend (n = 168)
No PHEVs	Gasoline (Gal.)	1,678,681	1,383,481	1,678,681	1,383,481
CS upgrade only	Gasoline (Gal.)	1,017,273	803,156	988,387	766,027
	% Gas reduced	39.4%	41.9%	41.1%	44.6%
Plug and Play	Gasoline (Gal.)	866,830	660,561	821,488	567,867.3
	% Gas reduced	48.4%	52.3%	51.1%	59.0%
	Electricity (MWh)	4,354	4,284	5,353	5,782
	Peak (MW)	596	384	705	520
	Peak Time	6:00pm	1:45pm	6:30pm	1:45pm
Enhanced Worker access	Gasoline (Gal.)	819,174	655,104	774,019	559,107
	% Gas reduced	51.2%	52.6%	53.9%	59.6%
	Electricity (MWh)	5,815	4,488	6,861	6,042
	Peak (MW)	559	384	625	524
	Peak Time	6:00pm	1:45pm	6:30pm	1:45pm
Off peak only	Gasoline (Gal.)	892,361	688,324	844,107	604,952
	% Gas reduced	46.8%	50.2%	49.7%	56.3%
	Electricity (MWh)	3,647	3,533	4,633	4,815
	Peak (MW)	365	353	463	482
	Peak Time	8pm-6am	8pm-6am	8pm-6am	8pm-6am

Time of day gasoline use corresponds to rush hour periods in Figure 11. In the Plug and Play scenario overall gasoline use is estimated to be half relative to the No PHEV scenario, Table 5. Gasoline use is reduced by a larger degree in the morning due to the higher proportion of miles driven in CD mode earlier in the day. Table 5 also shows that a large portion of this gasoline reduction (76 percent to 81 percent) is due to CS fuel economy.[7] For this reason, overall gasoline savings varies little across the three charging scenarios or the price levels in the design game; in all instances, gasoline use is cut in about half compared to the No PHEV scenario.

[7] However, simulating only CS fuel economy upgrades may be inappropriate—respondents might not have chosen the vehicle upgrades without plug-in and CD capabilities.

The peak magnitude and timing of charging varies across scenarios. Figure 20 plots all three charge scenarios. The Enhanced Worker Charging Access scenario increases overall electricity use by 34 percent relative to Plug and Play, with much of the addition occurring in the morning as drivers arrive at work. In contrast, the Off Peak Only scenario reduces electricity use by 16 percent, largely due to the elimination of work and other non-home charge opportunities that occur during peak hours. This scenario has the benefit of eliminating all electricity use during peak hours, with nightly demand balanced at 365 MW. As noted, the specific balancing strategy used in this scenario would likely vary by electric utilities to flatten out overall off-peak demand, as seen in Lemoine et al's (2008) optimal charging scenario. The researchers' scenario merely demonstrates the potential for shifting and minimizing peak demand.

Figure 16: Gasoline Use in No PHEV Scenario, Scaled for One Million Vehicles (Weekdays Only, Early Market Potential Respondents Only, n = 590)

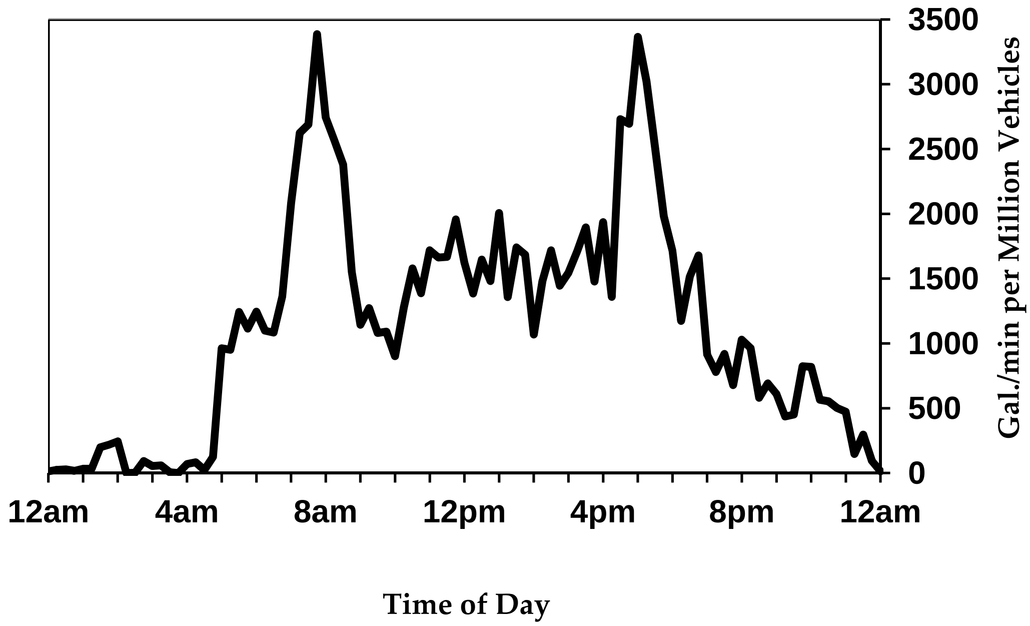


Figure 17: Energy Use in Plug and Play Scenario, Scaled for One Million PHEVs (Weekdays Only, Early Market Potential Respondents Only, n = 590)

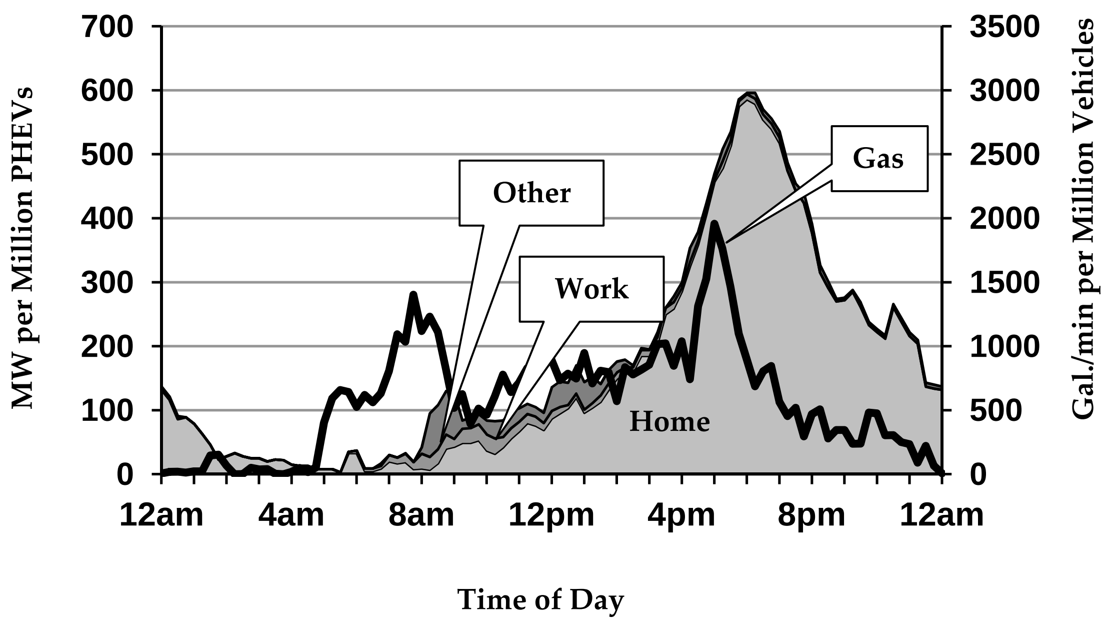


Figure 18: Energy Use in Enhanced Worker Charging Access Scenario, Scaled for One Million PHEVs (Weekdays Only, Early Market Potential Respondents Only, n =590)

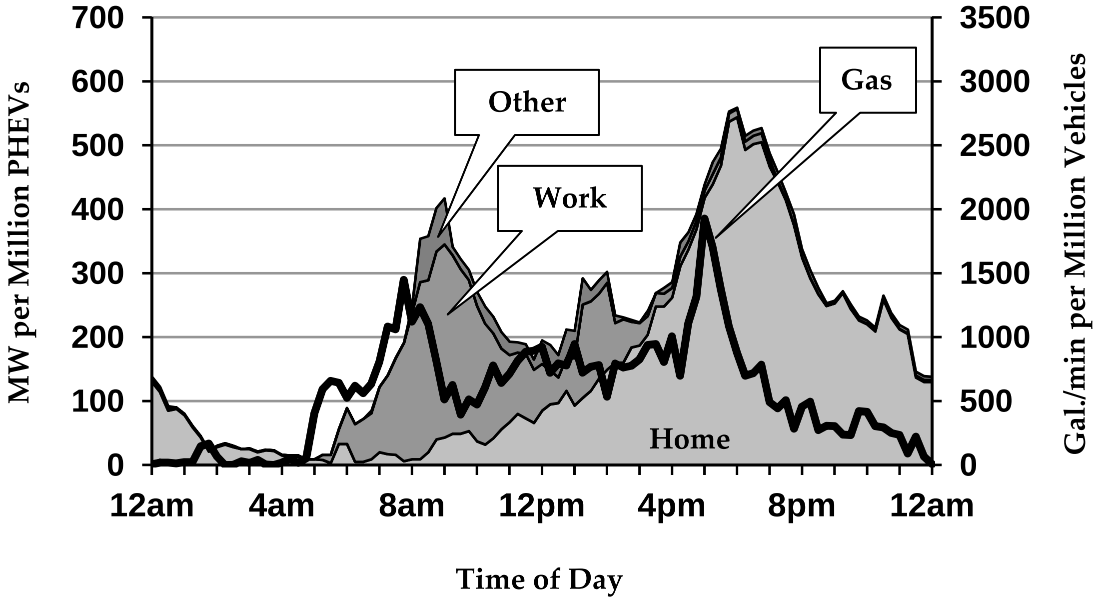


Figure 19: Energy Use in Off Peak Only Scenario, Scaled for One Million PHEVs (Weekdays Only, Early Market Potential Respondents Only, n =590)

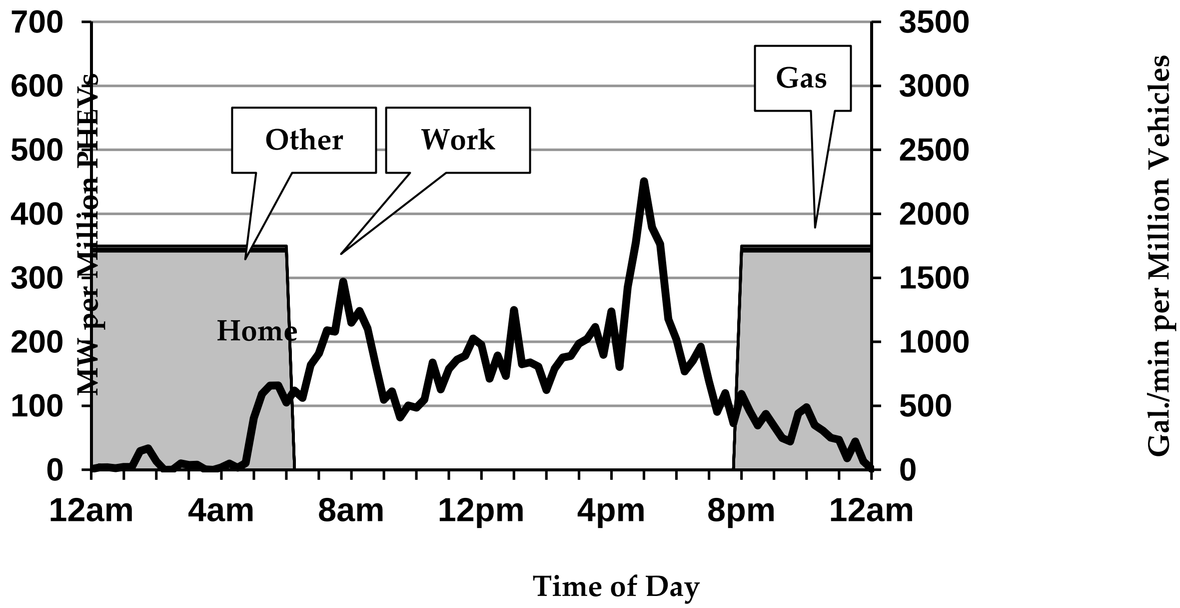
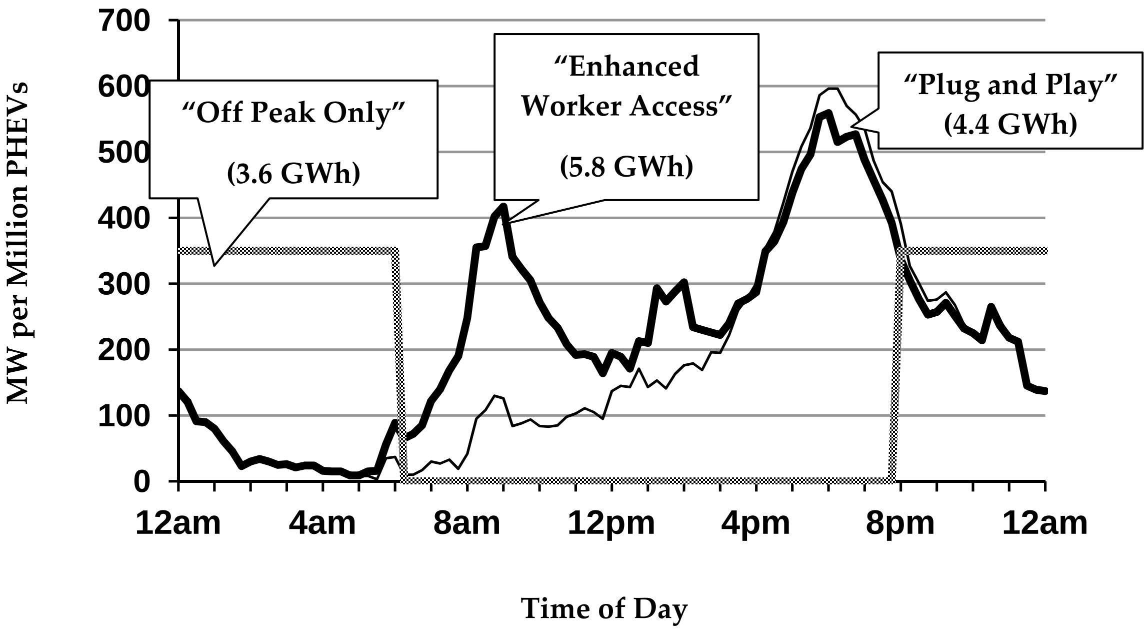


Figure 20: Comparing PHEV Charge Scenarios, Scaled for One Million PHEVs (Weekdays Only, Early Market Potential Respondents Only, n =590)



CHAPTER 3: A PHEV Demonstration and Market Research Project to Assess Consumer Valuation of PHEV Designs

This chapter reports on a research project designed to address the question, why would consumers buy plug-in hybrid electric vehicles (PHEVs)? An integrated set of demonstration, research, education, and outreach activities was deployed to provide a sample of California households with the requisite knowledge and experience to provide informed responses to PHEVs, thus overcoming one primary impediment to PHEV commercialization—a lack of understanding by consumers, vehicle designers, fuels providers, and regulators of consumers response to the driving, charging, and refueling patterns of PHEVs, that is, to what extent will drivers of PHEVs charge from the grid or refuel the internal combustion engine, and where and when will charging occur.

With substantial funding from the California Air Resource Board's Alternative Fuels Implementation Program (AFIP) and additional support from the California Energy Commission's Public Interest Energy Research (PIER) Program, the Plug-in Hybrid Electric Vehicle Research Center (PHEV Center) at the University of California, Davis implemented a PHEV Demonstration and Consumer Education, Outreach, and Market Research Project, hereafter referred to as the project. Other project contributors include the AAA Northern California, Nevada and Utah, and Idaho National Laboratory (United States Department of Energy).

3.1 Project in Context

The project is the third research activity in the multi-year, integrated research agenda described in the introductory chapter. The defining feature of PHEVs, the ability to plug the vehicle into the electrical grid and refuel it from another network of liquid or gaseous fuels, is the source of both their potential benefits and the uncertainty over whether their potential can be realized. Much of the appeal of PHEVs is based on the flexibility afforded by two energy systems. This flexibility offers new choices for consumers, from a range of vehicle designs, for example, size of battery and motor, as well as flexibility around the way the vehicle is used, for example, how often the battery is charged versus how often the liquid or gaseous fuel is refueled. To achieve and optimize the potential of PHEVs to reduce vehicle emissions and gasoline consumption, such as, to accomplish their societal benefits, PHEV owners will need to use electricity from the grid.

Consumers will be faced with a previously unknown set of capabilities and thus unfamiliar choices. For example, the larger the battery, the greater the percentage of their driving can be accomplished using electricity from the grid. On the other hand, the larger the battery the higher the initial price of the vehicle. As the initial vehicle price will be readily apparent, but the new and largely unfamiliar benefits only unfold in the future, sound policy and market actions depend on assessing potential consumers' response to these distributions of costs and benefits. Moreover, PHEVs can be engineered to suit different consumers or regulators; PHEVs can be designed to minimize CO2 reduction, provide high torque and acceleration, maximize battery life, maximize consumer control over the choice between electricity and gasoline, or some combination of these.

This discussion points to two facts that guide the design of this project. First, consumers are unaware of the potential advantages, disadvantages, new capabilities, and costs of PHEVs. Second, how consumers form their awareness, how they assimilate and process new knowledge about PHEVs, how they turn this awareness, knowledge, belief, and motivation into demand for PHEVs, and thus whether consumers will buy PHEVs, which type of PHEVs they would like to buy, and how they might drive, charge and refuel those PHEVs are all largely unknown.

3.2 Project Description

3.2.1 HEV to PHEV Conversions

Toyota Priuses were purchased and converted to plug-in operation using the Hymotion, now, A123 Systems conversion package. While such vehicle conversions are clearly only an interim step, they offer a test-bed for real world research with car-buyers. The A123Systems conversion involves the installation of a 5KWh lithium-ion battery in the spare tire well in the rear cargo area of the vehicle, as well as the necessary electrical and communications connections to incorporate the battery into the vehicle’s drive system and to charge the battery. The battery charges from a standard U.S. three-prong, grounded, 110-volt outlet. The charging point is in the left-rear bumper of the vehicle. A fully discharged battery can be charged in approximately five hours.

It is important to understand that the converted vehicle remains subject to the underlying control strategy of the OEM vehicle. Specifically, these PHEV-conversions are best described as operating in a manner that more or less continuously blends electricity and gasoline—though it is the case that while the conversion, or supplemental, battery is discharging, far more electricity is being used than in a conventional Prius and it is easier, though by no means easy, to drive so that the ICE remains off. Even while the supplemental battery is contributing to the propulsion of the vehicle, aggressive accelerations, speeds higher than 35mpg, and upward grades are likely to cause the ICE to start to meet the additional load.

Additionally, the vehicles were equipped with onboard data collection and transmission devices. The devices and the cellular service to transmit the data were provided to the project by INL. V2Green, Inc. (now, Gridpoint, Inc.) manufactured the data collection and transmission systems. They also port the data to a website that summarizes vehicle performance. UC Davis contracted for additional programming services to allow individual project drivers to track their performance.

The PHEV conversions were placed in households in northern California for several weeks at a time. Households were recruited with the assistance of AAA Northern California, Nevada, and Utah. The households were selected because they represent important markets segments and use patterns for PHEVs. The realized sample of project participants to date is described in the next section. During the households’ PHEV trial use periods, researchers collected data on travel, vehicle charging and refueling, performance of the vehicle, and participants’ response to the PHEV technology. Data were collected directly from the vehicle using on-board data systems, as well as from interviews, questionnaires, and fueling logs.[8]

3.2.2 Research Questions to Be Addressed in This Project

The project addresses the following questions.

1. What are the PHEV designs created by project households and how do these designs compare to those created by survey respondents who have no experience driving PHEVs?
2. What are the charging behaviors of the project households, and how do driving behaviors influence charging behaviors?
3. Given that project participants are driving one specific incarnation of what a PHEV can be, what are the effects on their transportation energy use?

3.2.3 Household PHEV Placements

PHEV-conversions are placed in households for periods of time that allow for the household members to learn and adapt. Starting in late-August 2008, household placements were initially scheduled for four weeks. After completing the research process with over twenty households, researchers judged that four weeks was not long enough for many of the households. In particular, some were still learning about charging and its effects on energy use and cost. Further, most households were still talking about the Prius per se, leaving less time to discuss the added plug-in capability.[9]

Starting in February 2009, households in the project used the vehicles for six weeks. The PHEV-conversion package allows for the conversion to be taken off-line, returning the operation of the vehicle to that of a conventional Prius.[10] Therefore, the PHEV-conversions were delivered to the households with the conversion off-line. The conversion was placed back on-line after two weeks. This allowed the households to respond to a more-or-less conventional Prius and then move on to experience and evaluate a particular PHEV. Further, the two-week pre-PHEV period allowed us to establish a baseline of driving performance based on data from the on-board data systems.

Participants were interviewed at the start of, during, and at the end of their PHEV trial to make sure the vehicles are working properly and to explore with the household their use of and response to the vehicle. The households completed a screening questionnaire, used in recruiting participants, and the first and third parts of the questionnaire previously administered to

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[8] The demonstration vehicles are instrumented to record travel and charging/refueling. Additionally, drivers complete a refueling log so we know how much was paid for gasoline.

[9] Of the households included in this report, only one was a pre-existing HEV owner. Additional HEV owners are being included in the subsequent sample.

[10] Because the conversion package adds weight, the Priuses in our demonstration—with the conversions off-line—return slightly worse fuel economy than unconverted Priuses.

representative samples of the U.S., California, and the counties along the Interstate 80 corridor from the San Francisco Bay Area to eastern suburbs of the Sacramento region. The last region was over-sampled in particular to provide a comparative population for the households participating in the project.

3.2.4 Interviews and Questionnaires

Each household was interviewed multiple times: upon vehicle delivery, every two weeks, and finally after the last week when the vehicle was retrieved. Interviews lasted between one and two hours. Two researchers attended the first and last interviews. All interviews were recorded; all but the first interview recordings were transcribed. The initial interviews tend to be given over to formally enrolling the household in the study—which must happen before the vehicle can be handed over and substantive interviewing can begin. During this first interview, researchers primarily listen for the questions the household has about the vehicle, offering answers that are as non-leading as possible. For example, every household asks how often the vehicle should be plugged in. The standard response is that these cars can be driven without ever being plugged in, but that what researchers are hoping to learn from the household is how often they plug-in and why.

The second and third interviews follow protocols, such as, outlines of topic areas to be covered with every household. Each topic area includes example prompts that are not used in every household, but only as needed or appropriate to each household. An example of the protocol is included in Kurani et al (2009), Appendix A.

In addition to the recruiting and screening questionnaire, each household in the project also completed a two-part online survey eliciting several types of data. The survey was slightly modified from the instrument administered to over 2,200 U.S. respondents as reported in Axsen and Kurani (2008). This previous study included over-samples of California (n= 851) and Northern California (n=216) in the region along Interstate-80 from the San Francisco Bay Area to the eastern reaches of the Sacramento conurbation. In this report, responses from these two samples are compared with the responses of project participants.

The primary survey instrument used in the PHEV project is the same set of two internet-based questionnaires completed by the national survey sample described in the previous chapter. In the case of the project households, the first was completed before they drive the PHEV, and the second consisting largely of the plug-in hybrid electric vehicle (PHEV) design games, was completed after the household has driven the PHEV for several weeks but prior to their final interview. As with the national survey sample, Part One includes questions on vehicle ownership, knowledge of gasoline use and spending, knowledge of electricity use and spending, awareness of electric-drive vehicles, attitudes towards environmental and global issues, as well as household structure, income, education and other demographic variables. Awareness of electric-drive vehicles is assessed with questions eliciting the stated familiarity of respondents with conventional gasoline, hybrid-electric, electric, and plug-in hybrid electric vehicles. Respondents were then asked to demonstrate their understanding by choosing how each vehicle type could be fueled: with gasoline, electricity through an electrical outlet, or either. The implication of this exercise is not that consumers need to have a deep technological understanding of electric-drive vehicles to buy them. However, researchers felt that basic familiarity, such as whether or not the vehicle can be plugged in, may shape participants experience with the PHEV-conversion during their trial period and ultimately affect their PHEV design priorities.[11]

The Part Two questionnaire focused on PHEV design priorities elicited in two versions of priority-evaluator games. To improve the quality of data gathered from project participants, prior to the PHEV design exercises, participants were provided a PHEV buyers' guide describing basic design options for PHEVs, replicated in Kurani et al (2009), Appendix B. Respondents then completed two PHEV design games, replicated in Kurani et al (2009), Appendix C. The first was a PHEV Development Priority game in which participants create PHEV designs over several iterations. Second was a Purchase Design game, similar to the first, but the design possibilities were priced in dollars and participants could reject buying a PHEV, instead retaining a conventional vehicle.

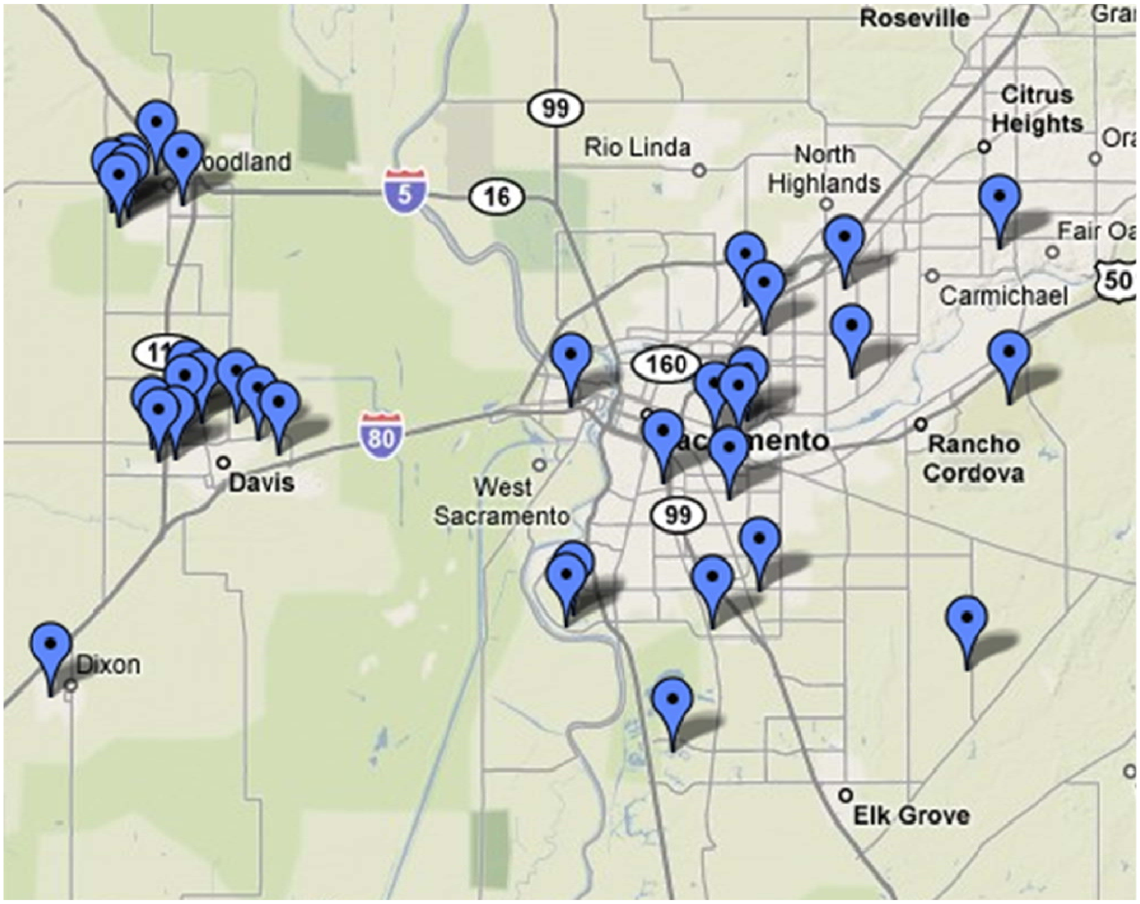
3.2.5 Who Are the Project Participants?

Participants were recruited through an illustrative sampling method (Turrentine and Kurani, 2007.) Such a sample does not attempt to be representative of a population; rather, the purpose is to illuminate the behavior of specific groups. The sampling frame for the project was defined by the following: 1) automotive insurance requirements, 2) geographic location, 3) vehicle ownership, 4) driving, and 5) broad categories of household structure.

Participants were selected for the project in a three-stage process. First, AAA Northern California, Nevada and Utah issued an invitation to their automotive policyholders who 1) met minimum requirements regarding the amount of insurance they carry and their driving records, and 2) live within the geographic region specified by researchers at UC Davis. Presently that region is roughly defined as the area within about 30 to 45 minutes driving time of Davis, CA. Second, volunteers from the recipients of the letter were instructed to log-on to a website hosted on a UC Davis server, where they completed a brief questionnaire which solicits more specifics of the potential participant's vehicles, home, travel, household, and contact information. Third, researchers reviewed the questionnaire responses and selected households based on the goal to illustrate the responses of different types of households. The geographic distribution of the participant households summarized in this report as shown in Figure 21.

[11] As asked of the prior national, statewide, and regional samples—who will not have experience with a PHEV afforded to Project participants—the question was intended only to test whether basic familiarity with electric-drive technologies affected PHEV design priorities.

Figure 21: Geographic Distribution of PHEV Project Participants (n=34)



To explore whether findings from the project can be generalized to other people, researchers describe briefly who the project respondents are and how they compare to other larger samples. These include the California and northern California over-samples researchers surveyed during the nationally representative survey of new car buying households. Other comparisons are made to the 2001 Nationwide Household Travel Survey, the 2005-2007 American Community Survey, and the 2000 United States Census.

Descriptions of the samples on the following attributes are presented in Table 6: household hybrid vehicle ownership, respondents' gender, education, age, household income, and housing type. One important difference between the project participants and all other samples is that project participants were chosen, in part, because they have a place at home to charge the PHEV—we judged it to be of little value to give a vehicle to a household who could not routinely and easily charge the vehicle, if they chose to. This choice on researchers' part will introduce some differences in income and housing type as seen in Table 6.

The gender balance of the present project participants represents that of the general population and California over-sample; the northern California over-sample is skewed toward male respondents. The project participants are skewed toward people with graduate educations—

even compared to researchers' survey over-samples, which are skewed toward higher education compared to the general population samples. Respondents in all three of the samples are much more likely to be between the ages of 35 and 54 than the general population; the skew toward this age group is even stronger in the present project sample than in the survey over-samples. As with education and age, the present sample of project participants amplifies the distinctions from the general population of the survey over-samples: the over-samples of new car buyers in California and northern California are more likely to have higher household incomes than the general population and the project participants are even more likely to have higher incomes. As noted above, by design (or rather, because of known correlations between housing type and ability to charge at home) the survey respondents are far more like to live in detached homes.

3.2.5.1 Gasoline Prices Faced by Survey Respondents and Project Participants

One question researchers are repeatedly asked regarding the national study is when was it done in comparison to the run-up of gasoline prices to past $4.00 per gallon during the summer of 2008? The answer is that the national survey was conducted in December 2007 and precedes the rise of gasoline prices past $4.00 per gallon by several months. The average price last paid for gasoline by the California and northern California samples were both about $3.40 per gallon as shown by the horizontal lines in Figure 22.

In contrast, the first project participants were paying well in excess of $4.00 per gallon for gasoline in August 2008. But these are a small minority of project participants, as prices quickly declined through September and October 2008 to, and then below, the average of the price faced by the national survey respondents. Still, whether they faced higher gasoline prices during their PHEV trial period or whether they simply recall such higher prices from last summer, researchers expect that project participants may be more sensitive to the uncertainty of gasoline prices than the national survey respondents were at that time. This may make project participants less like survey respondents, but makes them more like their peers, such as, all car-buying households, who have now lived through this same price history.

3.2.5.2 Motivations and Knowledge Regarding Electric Drive

The invitation sent by AAA Northern California, Nevada and Utah did not emphasize motivations to volunteer; still, one might speculate that the households volunteering for a PHEV demonstration project have stronger motivations and knowledge regarding electric-drive vehicles than households in general. Responses to three questions regarding motivations are summarized in Figure 23: global warming, air pollution, and energy (in)dependence. The project sample contains a slightly higher percentage of people who state that each of these three issues is a serious problem, and immediate action is necessary than in the California and northern California survey samples. Still the differences are small. Researchers judge the differences to be unlikely to make a substantive difference in any conclusions researchers may draw between the samples on their PHEV designs.

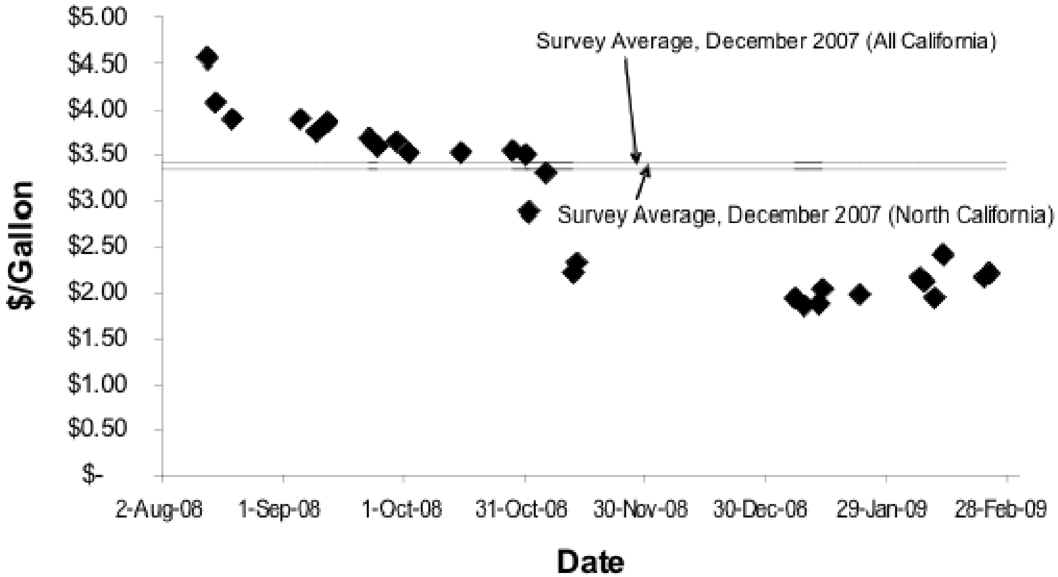
Table 6: Comparing Project Participants, Survey Respondents, and the General Population

Target		AAA members	New vehicle buyers			General population	
Year		2008-9	2007	2007	2001	2005-7	2000
Data source		PHEV Demo	PHEV Survey (Nor. Cal.)[a]	PHEV Survey (Cal.)[a]	NHTS[b] (Cal.)	ACS[f] (Cal.)	Census[g] (Cal.)
Sample size		34	216	851	389		
Hybrid owner?	Yes	11.8%	8.9%	10.6%	-	-	-
Gender[c]	Male	49.2%	59.7%	48.5%	44.5%	50.0%	49.7%
	Female	50.8%	40.3%	51.5%	55.5%	50.0%	50.3%
Education[d]	High school or lower	9.1%	2.6%	8.8%	22.1%	43.0%	43.3%
	Some college	21.2%	34.9%	33.9%	22.1%	20.4%	22.9%
	College degree	30.3%	32.8%	39.5%	39.9%	26.3%	24.2%
	Graduate degree	39.4%	29.7%	17.8%	15.9%	10.4%	9.5%
Age[c]	15 to 24	3.2%	4.6%	3.3%	6.5%	19.0%	18.3%
	25 to 34	8.1%	21.1%	20.5%	18.0%	18.3%	19.8%
	35 to 44	25.8%	27.3%	29.0%	23.5%	19.3%	21.6%
	45 to 54	27.4%	29.4%	23.7%	24.8%	17.6%	16.5%
	55 to 64	29.0%	10.8%	15.1%	13.3%	12.1%	9.9%
	>64	6.5%	6.7%	8.3%	13.8%	13.8%	13.8%
Household income	< 30 k	3.1%	1.8%	2.0%	6.3%	25.3%	31.2%
	30 k to 60 k	15.6%	11.9%	17.6%	23.4%	25.8%	29.5%
	> 60k to 100k	15.6%	35.1%	27.7%	32.3%	23.0%	22.1%
	> 100k	65.6%	51.2%	52.7%	38.0%	25.8%	17.3%
	Mean income[e]	$117,734	$106,949	$104,814	$84,416	$73,944	$61,441
	Ratio of mean incomes (new vehicle buyer/gen. pop.)	1.59	1.45	1.42	1.37		
Housing type[d]	Detached house	94.1%	71.3%	68.1%	79.4%	58.0%	
	Attached house	5.9%	10.3%	11.9%	4.4%	7.0%	
	Apartment	0%	17.9%	16.7%	13.6%	30.7%	
	Mobile home	0%	0.5%	3.4%	2.6%	4.2%	

[a] U.S. weights provided by Harris Interactive.

[b] NHTS sample limited to responding California households that had purchased a vehicle of model year 2001 or 2002.
[c] For PHEV project: data reported for all participants; for PHEV survey: data only reported for responding member of household.
[d] For PHEV project and PHEV survey: data only reported for responding member of household.
[e] Mean approximated from the product of middle values assigned to each income category and the proportion of the sample in that category.
[f] 2005-2007 American Community Survey 3-year estimates, California.
[g] 2000 Census by the U.S. Census Bureau.

Figure 22: Comparing Gasoline Prices From Survey Respondents (Lines) and Project Participants (Diamonds)



On the issue of knowledge regarding electric-drive vehicles, a question in the first part of the questionnaire completed by both the survey sample and project participants asked respondents to rate their familiarity with conventional, electric, hybrid-electric, and plug-in hybrid vehicles. This was followed up by a question asking how each of these four types of vehicles are fueled and/or charged. Responses to this second question are summarized in Figure 24. In general, there is little to distinguish the knowledge of electric drive vehicles among the project participants from the survey respondents—except on the specific issue of plug-in hybrids. Across all samples, very high percentages of respondents know that a plug-in hybrid can be both fueled and plugged-in; the highest percentage is among project participants. There are a few opportunities for information leaks to the project households about PHEVs—the recruiting phone call and the information provided to households when the PHEV is first delivered.

3.3 PHEV Designs

All participants in the project and in the prior survey research created PHEV designs. Researchers use these designs as measures of what is interesting and valuable to respondents about PHEVs. In addition to researchers' inherent interest in the PHEV designs created by the project participants, researchers are interested in whether and how the project participants' designs differ from those created by the prior survey respondents.

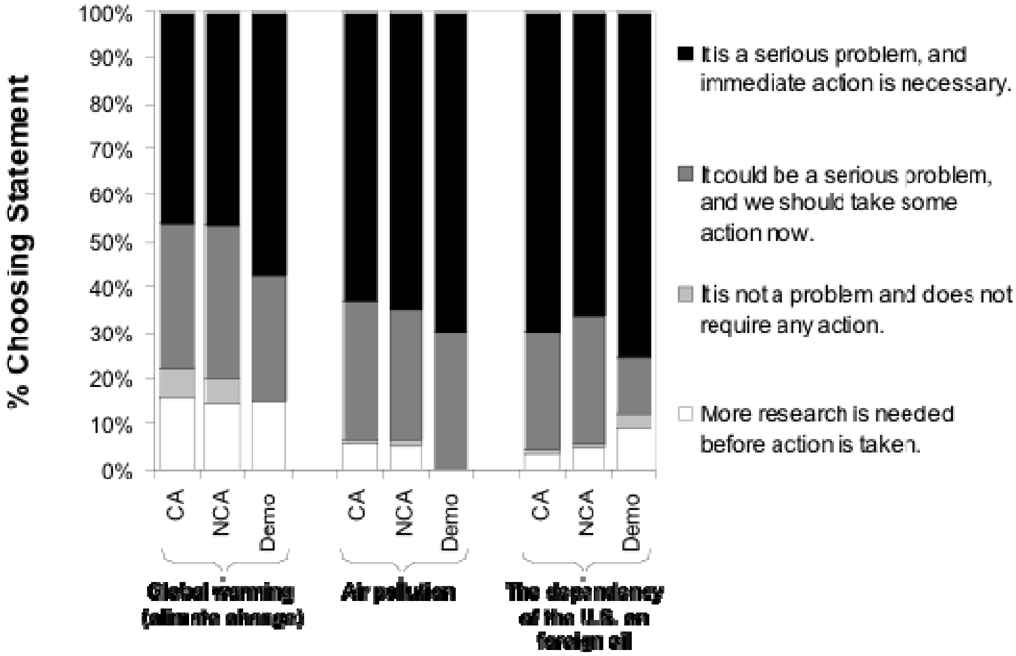
3.3.1 Who's PHEVs? Plausible Early Markets

This section compares the PHEV designs elicited from the 34 households who completed their project participation between August 2008 and April 2009 with those elicited from respondents in the California (CA) and northern California (NCA) over-samples of the national survey in

December 2007. The PHEV design games were described in the previous chapter. In this section, PHEV design priorities are reported only for respondents classified as plausible early market PHEV buyers by satisfying two requirements: 1) they demonstrate access to sufficient charge infrastructure, defined here as home access to an electrical outlet for their vehicle, and 2) interest in PHEVs as indicated by a reported purchase intention in the higher price condition of the Purchase Design game. Based on these conditions, Axsen and Kurani (2008) described 33.5 percent of responding U.S. new car buyers as plausible early market respondents. In the California over-sample, 45.8 percent of respondents park their vehicle within 25 feet of an electrical outlet at home, and of these, 73.5 percent indicate PHEV purchase intention in the higher price scenario, and thus 33.7 percent of the total California sample are classified as the plausible early market respondents (n=286). In the northern California over-sample, 45.6 percent have home charge access, 71.3 percent of which indicate a PHEV purchase intention, and thus 32.5 percent of the total sample is classified as plausible early market respondents (n=63).[12] Among the PHEV project participants, all have access to home charging because it is a requirement for participation. Among these 34 households, 30 (88 percent) indicate a PHEV purchase intention in the higher price scenario and thus these 88 percent are included as the plausible early market project participants. Clearly nothing about the likeliness to design a PHEV as their plausible next new vehicle purchase distinguishes the California and Northern California survey samples from the national sample; equally clearly, project participants are more likely to design their next new car as a PHEV. Given they are more likely to design a PHEV, are project households designing different PHEVs than did survey respondents?

[12] Because of the small samples for the households who completed their Project participation by April 2009 and for the plausible early market respondents in northern California, the comparisons made here are descriptive and exploratory rather than (necessarily) representative.

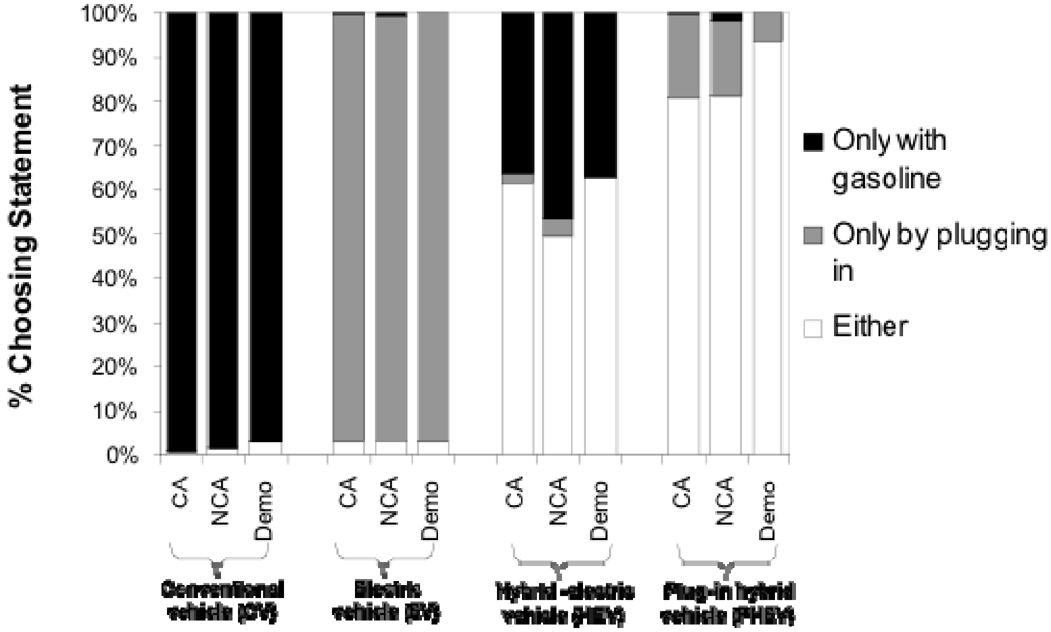
Figure 23: Comparing Environmental Beliefs Among Survey Respondents (CA and NCA) and Project Participants (Demo)



3.3.2 What PHEVs Do They Design?

The PHEV Purchase Design game first asks households to select a vehicle they were most likely to buy next. Figure 25 compares these base vehicles selected by survey respondents with those selected by project participants. Notably, 67 percent of project participants selected some variety of HEV and 40 percent selected a Toyota Prius. These percentages are 2 to 3.5 times higher than those of the CA and NCA samples, indicating a much more frequent interest in hybrid vehicles among project participants (after their PHEV trial) than was elicited from a broader samples of CA and NCA car buyers, who lacked direct experience with a PHEV. This difference may not be due to a predisposition and/or self-selection of project participants. Recall from their previous description that project participants are not substantially more likely to own a hybrid, do not possess more knowledge about electric drive vehicles, and do not have more concern for environmental or global issues—at least not to such a degree as to warrant a 2fold to 3.5 fold increase in hybrid interest in these design games. One explanation supported by the household interviews is that because project participants completed the PHEV Purchase Design game after driving the PHEV-conversion for several weeks, participants had become more interested in hybrids in general, and in the Toyota Prius in particular.

Figure 24: Comparing Electric-Drive Knowledge Among Survey Respondents (CA and NCA) and Project Participants (Demo): From What You Understand of These Vehicle Technologies, Which Can Use Fuel, and Which Can Be Plugged In?



Focusing on the interests of these plausible early market project participants, results of the two PHEV design games are summarized in Figure 26. In Round One of the Development Priority game, respondents were given one point to allocate towards one upgrade to the base PHEV model. As described previously, four upgrades were available in the first round of the game: charge time (from 8 hours to 4 hours), gasoline-fuel economy during CD mode (from 75 mpg to 100 mpg), CD range (from 10 miles to 20 miles), or CS gasoline-fuel economy (from 10 mpg to 20 mpg over the conventional version of the vehicle). Improving the CD range was the most frequently chosen upgrade (50.0 percent), while improving CS fuel economy was a close second place (39.3 percent).[13] The general ranking of attribute upgrades in Round One continues through later rounds: a higher percentage of potential early market respondents designed PHEVs with CD range upgrades and CS fuel economy upgrades, as well as CD type in later rounds, and few respondents designed PHEVs with faster charge times.

[13] Although the percentages add up to 100 across the columns in Round One, they do not in further Rounds because respondents have enough points to choose multiple upgrades.

Figure 25: Comparing Base Vehicles Chosen for PHEV Purchase Design Game (Plausible Early Market Only: CA, n=286; NCA, n=63; Project, n=30)

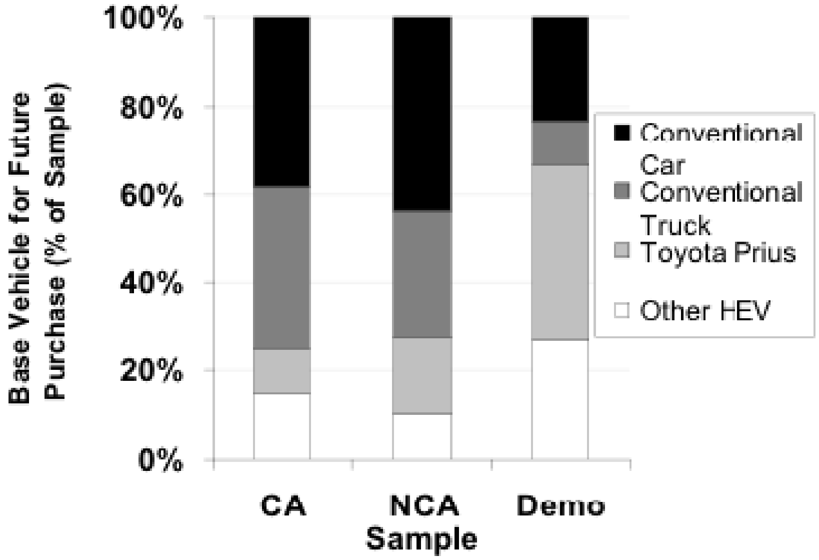
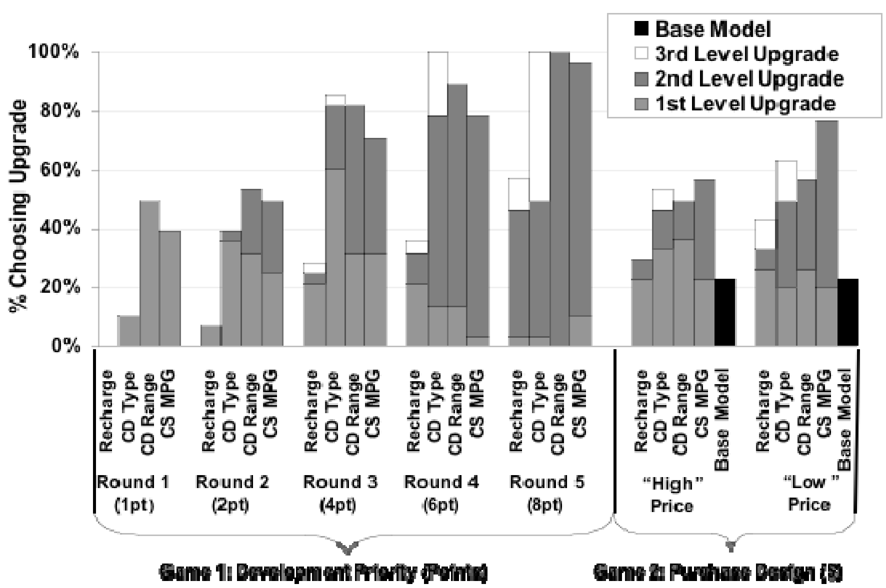


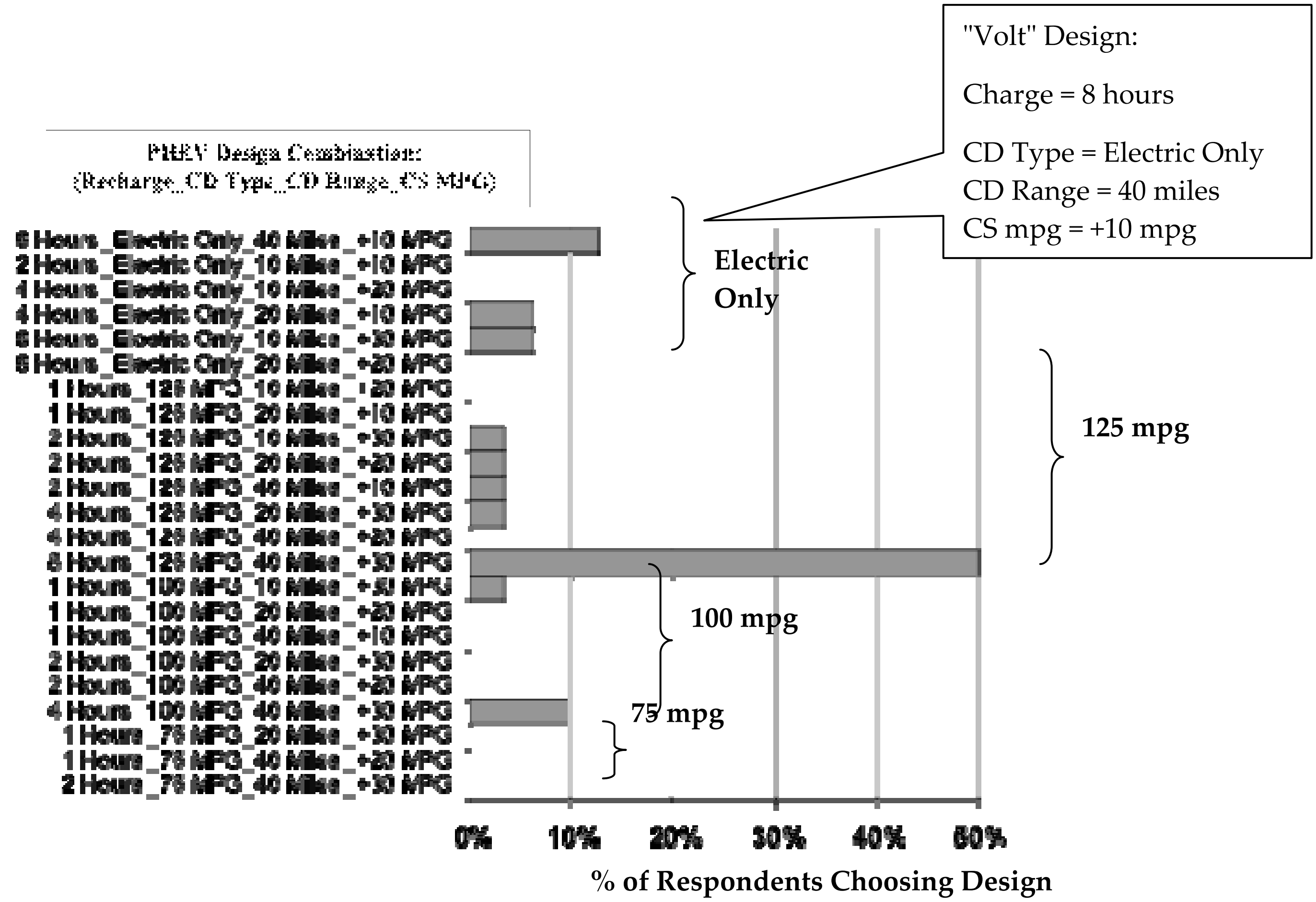
Figure 26: Upgrades Selected in PHEV Design Games by Project Participants (Plausible Early Market Project Participants Only, n=28)



All-electric operation (in CD mode) was first offered to respondents in Round Three of the Development Priority game; only one of the 28 households (3.6 percent) incorporated this upgrade into their PHEV, which came at the expense of any other upgrades available in prior rounds.[14] In Round Four, the number of plausible early market project participants designing a PHEV with all-electric operation rose to six (21.4 percent). Figure 27 portrays the 23 different possible PHEV designs possible in Round Four. This is the first round in which the design envelope allows a PHEV with 40 miles of all-electric range—a vehicle performance (at least as measured by CD mode and range) similar to GM's Volt concept. Only three of plausible early market project participants (10.7 percent) created this specific design. Overall, all-electric operation was not frequently incorporated into participants' PHEV designs when points were relatively scarce and alternative design possibilities were available, such as in Rounds Three and Four of the Design Priority game. PHEV performance priorities varied substantially; no single PHEV design emerged as a majority favorite. Still, the project sample to date is the most heavily skewed toward a single design, such as, 8 hours charging, 125mpg for 40 miles in CD operation, and +30 mpg in CS operation.

[14] Although 30 households were previously identified earlier as the plausible early market PHEV demo participants, data from the development priority game (game 1) are only reported for 28 households due to missing data (Figure 10, Figure 11, and Figure 13).

Figure 27: Distribution of Selected PHEV Designs in Round Four of Development Game (Plausible Early Market Only: Project, n=28)



As previously noted, results of the Purchase Design game suggest that the majority of project participants would value PHEV capabilities in their next vehicle. Figure 26 also depicts the proportion of upgrades chosen in the price conditions for this second version of a PHEV design game. Seven of plausible early market project participants, 25 percent, chose the base PHEV models with no upgrade in both price conditions. Among those who created higher cost designs, overall patterns of these designs are similar to those created in the Development Priority game; CS fuel economy upgrades were chosen more often than other upgrades, and there is no evidence of the strong interest in all-electric operation observed among some pioneer PHEV conversion drivers (Kurani et al., 2007). All-electric upgrades were chosen by two households (seven percent) and four households (13 percent) in the higher and lower price conditions, respectively.

Figure 28 depicts the proportion of CD type and CD range designs selected by project participants. Note that 11 households (37 percent) designed a PHEV capable of 75 mpg for the first 10 miles, and that 24 households (86 percent) designed a blended CD design, as opposed to all-electric, with a range of 20 miles or less. Such designs have far lower battery requirements than the all-electric, longer-range designs assumed by various battery experts (Axsen et al., 2008).

Figure 28: Distribution of Selected PHEV Designs in High Price Scenario of Purchase Design Game (Plausible Early Market Project Participants Only, n=30)

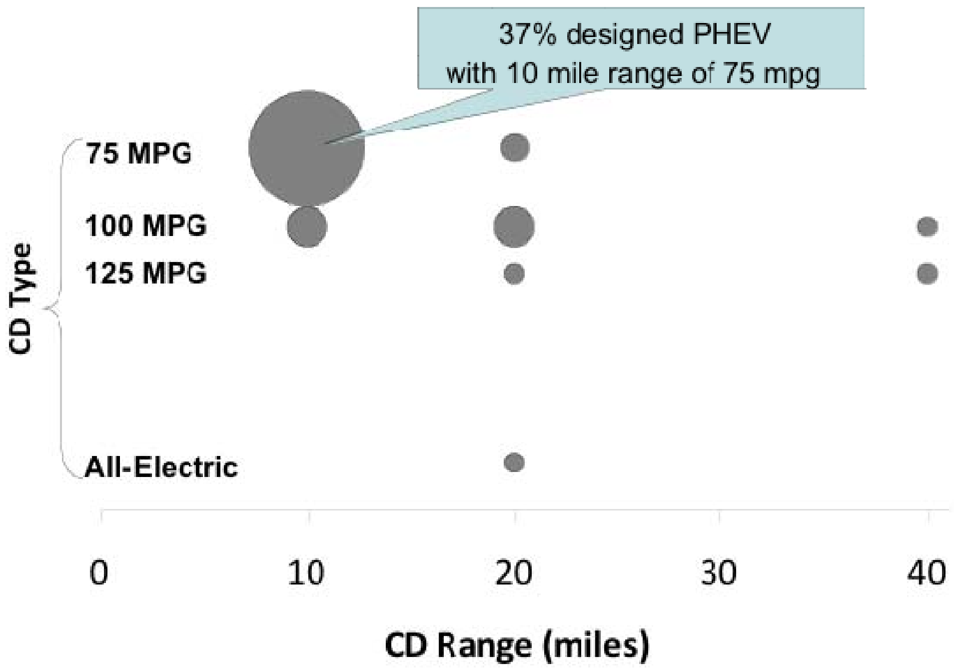


Figure 29 compares Round 4 of the Development Priority game results from plausible early market project participants with those respondents from the CA and NCA samples. Results are fairly similar across samples, though project participants selected charge upgrades less frequently, and selected 100 CD mpg and +30 CS mpg more frequently. Figure 30 and Figure 31 show the distribution of PHEV designs in Round Four in the CA and NCA samples, respectively.

Figure 29: Comparing Upgrades Selected in Round 4 of Development Priority Game, (Plausible Early Market Only: CA, n=286; NCA, n=63; Project, n=28

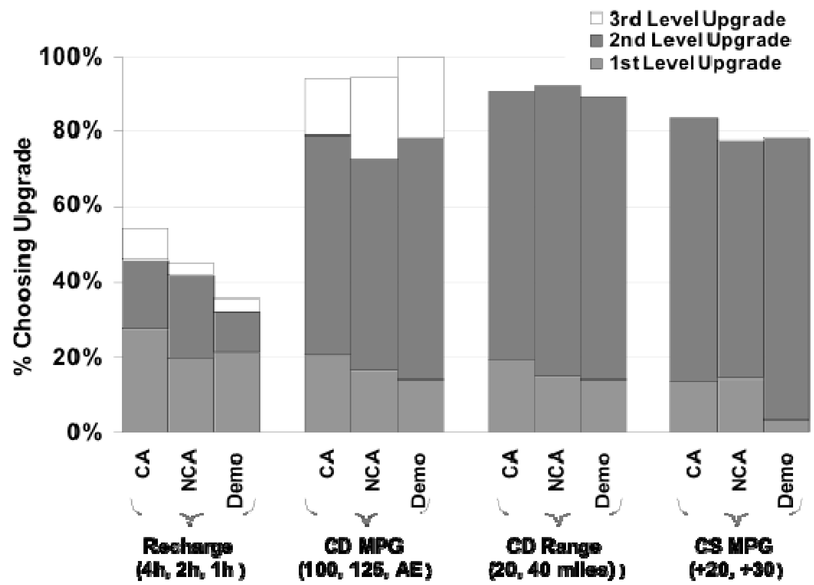
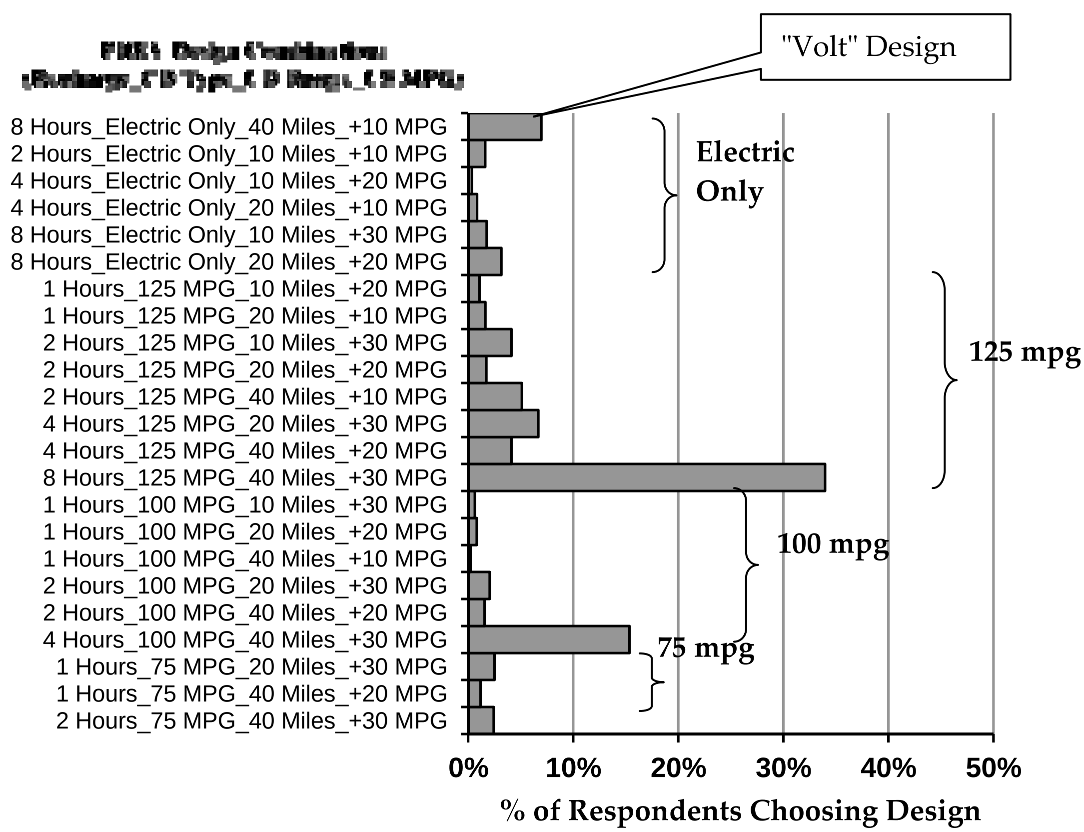
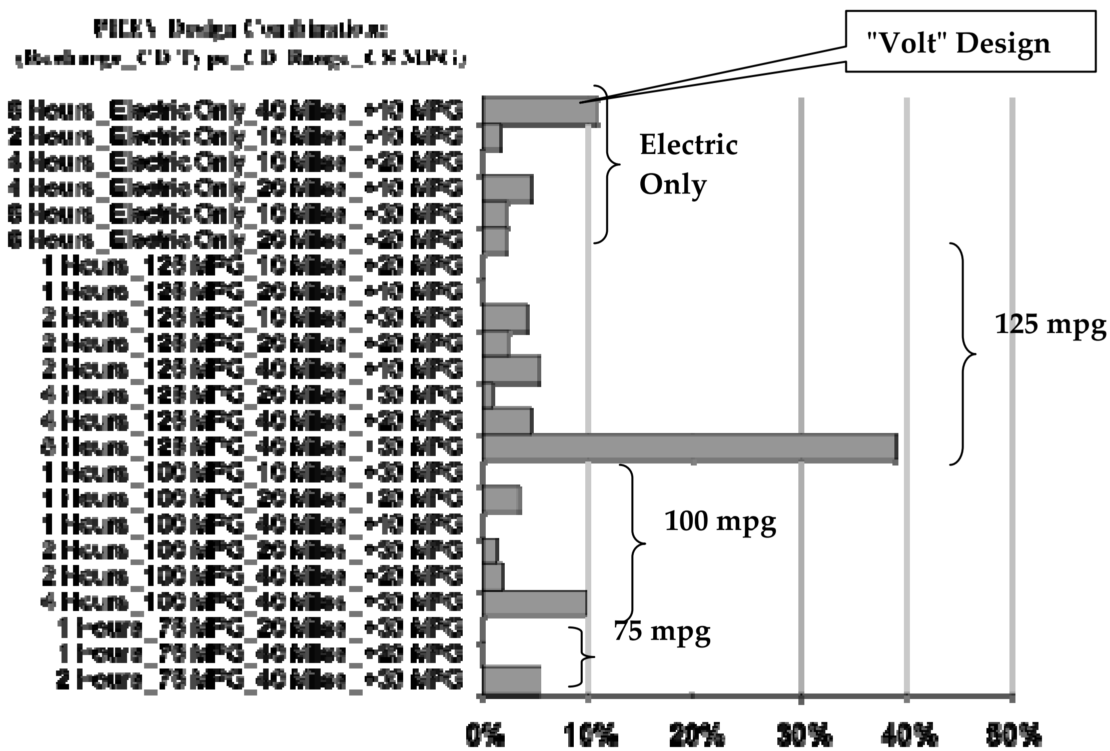


Figure 30: California Distribution of Selected PHEV Designs in Round Four of Development Game (Plausible Early Market Only: CA, n=286)



All figures indicate a wide variety of PHEV design interests among households, without any particular draw to the all-electric 40-mile Volt concept. Figure 32 compares the same samples in terms of the higher price scenario of the PHEV Purchase Design game, where a substantially higher proportion of project participants selected some level of CD type and range upgrades. Several differences among samples could contribute to this trend; project participants have: higher household income, Table 3 and more experience with PHEV driving, having actually driven a PHEV for several weeks, as well as other potential differences in driving patterns, commute patterns or other factors that were not measured in all three samples.

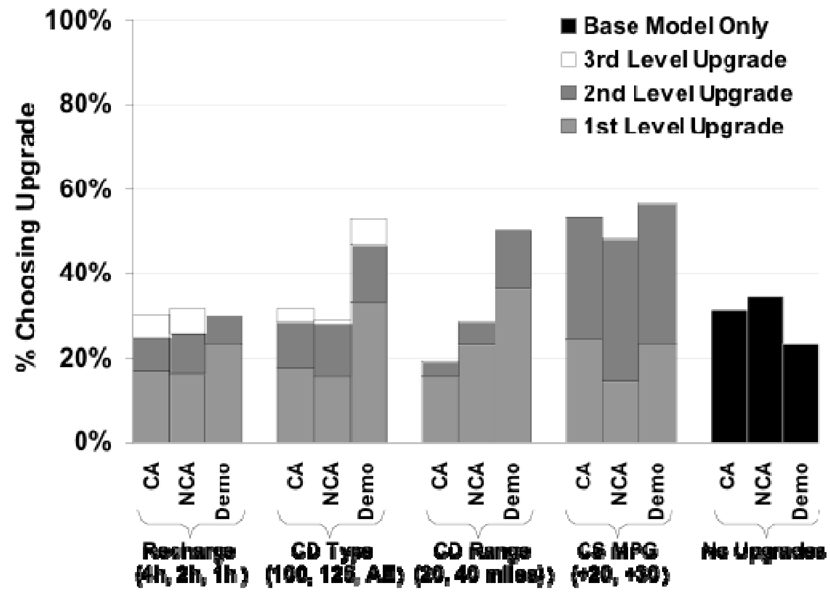
Figure 31: Northern California Distribution of Selected PHEV Designs in Round Four of Development Game (Plausible Early Market Only: NCA, n=63)



3.4 Charging Frequency, Time of Day, and Location

Drivers in this project have the option of charging a vehicle to decrease gasoline use and increase electricity consumption for the duration of the supplemental battery's charge. Recall, the PHEV-conversions used in this project provide blended operation in CD mode: the cars are still subject to the underlying HEV hardware and software. During CD mode these PHEV-conversions will blend in more electricity than does a conventional Prius (which operates only in CS operation). Like a conventional Prius, it is practically difficult to achieve sustained all-electric driving in real-world conditions.

Figure 32: Three-Sample Comparison of Upgrades Selected in Higher Price Scenario of Purchase Design Game (Plausible Early Market Only: CA, n=286; NCA, n=63; Project, n=30)



% of Respondents Choosing Design

All figures presented in this section are based on the last week of each household's trial with the PHEV conversion. This provides a common period over which researchers can compare the same number of days and days of the week from each household. Also, the last week represents the highest degree of uniformity of understanding about charging behavior across the households. Finally, since researchers judge that the households had developed their charging habits by this last week or had developed their habits as much as they were going to in the course of their PHEV trial, researchers view their final week with the PHEV as most representative of how these vehicles would be charged by the households in the future. This judgment is generally confirmed by the household interviews.

Perhaps more than any other information presented in this report, readers are cautioned against generalizing observations here to all PHEVs and users. Daily life provides rhythms and routines that might shape behavior, for example the PHEV charging frequency discussed next. Researchers believe that PHEV charging behavior may also be shaped by the relationship between personal and household travel on the one hand and PHEV designs, especially all-electric versus blended CD operation and CD range, on the other. For example, while the weight of evidence gathered so far in this project suggests that households owning PHEVs will, on average, plug-in the PHEV more than once per day in an unconstrained world, researchers are not yet prepared to dismiss the argument that if these households had been given PHEVs electric grid may be different than what was observed.[15]

3.4.1 How Often Do People Plug-in Their PHEV-Conversions?

The frequency with which people plug-in PHEVs to the electrical grid is perhaps the central daily behavior affecting the energy, environmental, and social benefits of PHEVs. Other important behaviors include the purchase of a PHEV whose CD range allows the household to accomplish the greatest proportion of miles driven in CD mode, constrained by the expense of buying too much CD driving range, before their next charge opportunity and driving behaviors affecting overall efficiency, notably accelerations, top speeds, and routes. The context for interpreting the PHEV charging behavior observed in this project is as follows.

1. The only participants in this project are people who can charge a PHEV at their home.
2. As most households lacked a sense of the etiquette that would shape charging at away-from-home locations, less away-from-home charging was observed than may otherwise occur in a world where the rules and conventions are known. Households who noticed EV parking and charging spaces often asked us whether they could park and charge their PHEVs in such spaces. The few bolder individual who tried discovered that such spaces presently lack 110-volt outlets suitable for the PHEVs they were driving. Many people said they were uncertain of the propriety of asking friends, acquaintances, and business-owners to charge.
3. No household was provided with time-of-day electricity tariffs.
4. The previous two are related in that some away-from-home charging opportunities such as workplaces would most often be used during the day (when electricity rates would presumably be higher, especially during afternoons and early evenings, under time-of-day electricity tariffs). PHEV drivers would then face countervailing signals—maximizing their PHEV benefits by plugging in more, but having to pay a higher price than nighttime electricity to do so.

In short, the charging frequency data reported here are from households who can charge at home, whose charging frequency is constrained by a general lack of away-from-home charging opportunities created by the lack of both physical infrastructure and social norms, but unconstrained by differential electricity prices.

Researchers calculated the mean number of times per day each household plugged-in their PHEV on weekdays and weekend days and plotted the resulting frequency distributions in Figure 33. The figures are based on only the final week of each household's experience with the

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[15] We use the phrase "plugging-in" to refer to all acts of connecting the vehicle to the electrical grid, regardless of the final state of charge of the battery when the vehicle is unplugged. We do this to create a more general category that contains both "charging," with its connotations of returning the battery to 100 percent SOC, and partial charging, in which the vehicle is unplugged and driven before the battery reaches 100 percent SOC.

PHEV-conversion. The weekday distribution ranges from zero to 2.6 instances of plugging-in per day. The zero-value for weekdays is from one household who determined that charging made too little difference to make it worthwhile, compared to the substitution of an HEV into their household fleet. The mean of the weekday distribution is slightly more than one plug-in event per day (1.05), 14 households (41 percent) were plugging in their PHEV more than once per day, on average across weekdays.[16]

Plugging-in occurs less frequently on weekend days than on weekdays. Notably, one-fourth the sample did not plug-in their PHEV on either weekend day; the high-end of the range was 1.5 times per weekend day. The mean number of times a PHEV was plugged-in per household was 0.82 per weekend day; nine households (27 percent) did so more than once per day. The two biggest causes of the lower mean weekend frequency were 1) the absence of charging at work by two households, such as, two households who plugged in at least twice a day on weekdays because they were plugging-in at home and work charged less frequently on weekend days because work was not available to them as an alternative charging location, and the higher likeliness in several households of not charging at home on weekends because the PHEV was not at home at least one weekend evening. The PHEVs were often taken on out-of-town trips on weekends, but were rarely if ever charged during these long, and often overnight, trips.[17]

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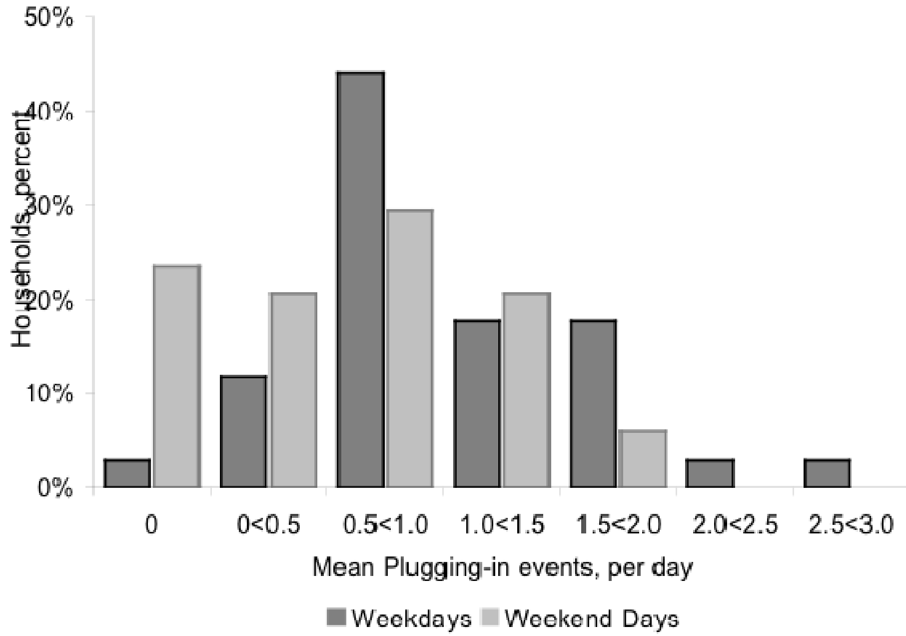
[16] We observed a difference in mean charging frequency across weekdays from a high of 1.24 charges per household on Wednesday to a low of 0.88 on Thursday. However, we presently regard this fine a level of analysis to be provisional and hypothetical

[17] The latter reason is supported by the fact that the average number of charging events per household was higher on Sundays (0.94) than Saturdays (0.71)—consistent with a PHEV returning on Sunday from an overnight trip that started on Saturday. As in the prior footnote though, such differences between days are provisional, and in this case must be regarded as supportive but not conclusive evidence.

Figure 33: Mean Daily Household Charging Frequency Distributions, Weekdays and Weekend Days, Percent



3.4.2 Electricity Availability and Instantaneous Power Demand

To describe charging behavior observed during each household's demonstration, researchers have summarized information in two additional measures: electricity availability and instantaneous power demand. Researchers defined electricity availability as the time of day during which the vehicle was plugged into an electrical outlet. Conceptually, this means that the vehicle could be at any stage in its charging cycle, available battery capacity, or at any location, so long as it is connected to the grid, electricity is available to the vehicle. Researchers define instantaneous power demand as the power drawn from the grid to charge the supplemental PHEV battery. The average charging rates for these PHEV-conversions varied across households—generally falling between 900 and 1200 watts. In order to compare and summarize across households, instantaneous power demand is standardized (by assumption) to be a nominal 1000 watts. Additional parasitic loads from the battery cooling system, in the range of 30 to 50 watts, and brief periods of higher demand during the initial phases of battery charging and longer periods of lower demand during trickle charge at end of the charging cycle are ignored.[18]

[18] When we have ascertained whether the differences in the observed average charging rates are due to differences across electrical outlets, vehicles, or both, we will provide a more refined analysis of power demand. Still, the broad behaviors described here have greater import for other analytical work than do the precise specifications of power demand for the specific combination of battery and charger employed in these particular vehicles.

The electricity availability and instantaneous power demand are represented as the percentage of vehicle users plugged in and the average instantaneous power demand (summed across households) at a specific time of day respectively, between 12:00 AM to 12:00 PM across all weekdays and weekend days. Average electricity availability and summed instantaneous power demand for every day of the week are in the Appendix E.

3.4.2.1 Electricity Availability and Instantaneous Power Demand: All Weekdays

Researchers treated all households' last week of driving the PHEV as if it had occurred during the same calendar week and all weekdays as if they were equivalent. Figure 34 displays the percentage of vehicles plugged in at a given time of day for all weekdays (in red, and on the left axis) and the instantaneous power demand summed over the households and averaged over weekdays (in blue, and on the right axis). As the red line shows, across the 170 weekdays represented in Figure 34 (34 households times 5 weekdays), 70 percent of households had plugged in their PHEV between 10:00 pm and 6:00 am. By 9:00 am only 20 percent of households had their PHEV connected to the grid. This can be explained by the number of respondents in the project that have full time jobs, and typically leave home in the morning to go to work. While two households charged during the day while at work, the other PHEVs plugged-in to the electrical grid during midday were due to retired individuals and teleworkers who typically were at home during the day. At 4:00 pm, when households start to return home from work, vehicles begin to be plugged in, until 10:00 pm by which time the percentage of households who have plugged in their PHEV stabilizes again at about 70 percent.

As Figure 34 represents an average from all participants' weekdays during their last week, it is not a representation of actual daily behavior. Daily electricity availability varied within each household from day to day. Figure 35 represents the observed variability in when households plugged in their PHEVs on weekdays, showing the low and high values for the percentage of vehicles plugged in for all weekdays by time of day. The bottom edge of the red area represents the low values observed at each point in time, and the top edge, the high value. For the time period between midnight and 6:00am, the lower values are predominantly due to the charging behavior on Monday nights. The greatest difference—in excess of 30 percentage points—between low and high percentages of households plugging in their PHEV occurs during the early evening, and reflects the variability both 1) within and across households in when they plug in the vehicle in the evening and; 2) variation across different days of the week. The lower boundary of the electricity availability during the evening is largely defined by Friday when more people tended to plug in the PHEV later in the evening.

While the electricity availability indicates when the vehicles were connected to the grid and could charge from the electric grid or discharge to the grid, it does not differentiate between the two. The blue line in Figure 34 shows the average weekday instantaneous power demand by time of day. Instantaneous power demand is derived by summing the power demand created for every day of the week by time of day for all participants' last week, and averaging across all five weekdays to create an average weekday. Given driving and charging behavior by the project households, electricity demand to charge their vehicles ramps up at 5:00pm and peaks just after 10:00pm. It declines steadily through the rest of the night and into the morning, reaching practically zero by 5:00am. While there were several households that charged during the day at work, most of the demand to charge these vehicles was between 9:00am and noon.

Figure 34: Electricity Availability (Percent of PHEVs Plugged-in) and Instantaneous Power Demand by Time-of-Day (Watts), Weekday Average

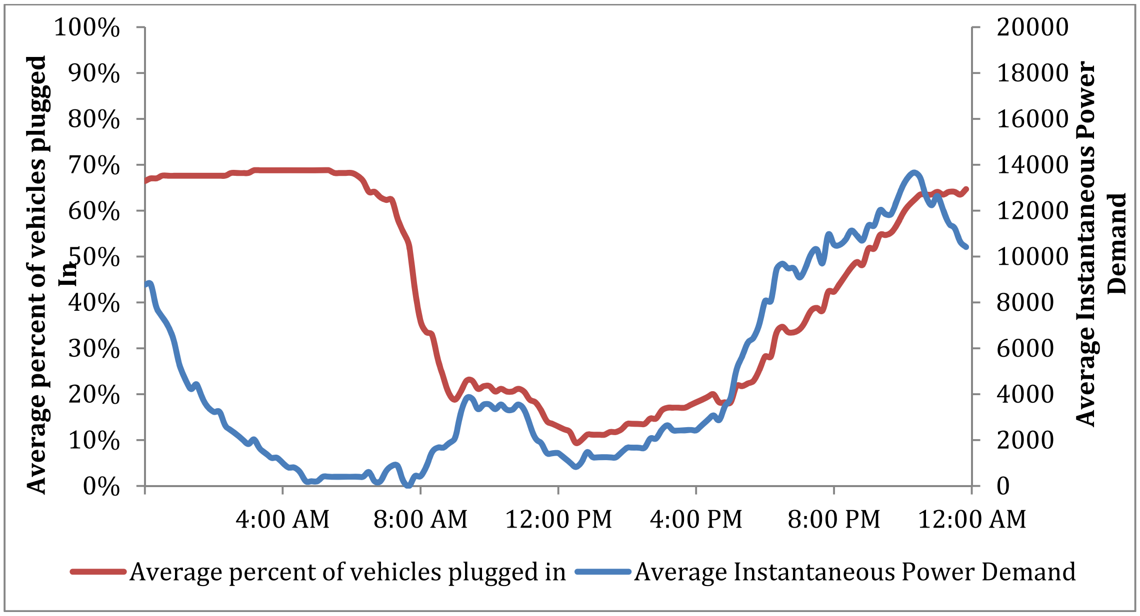
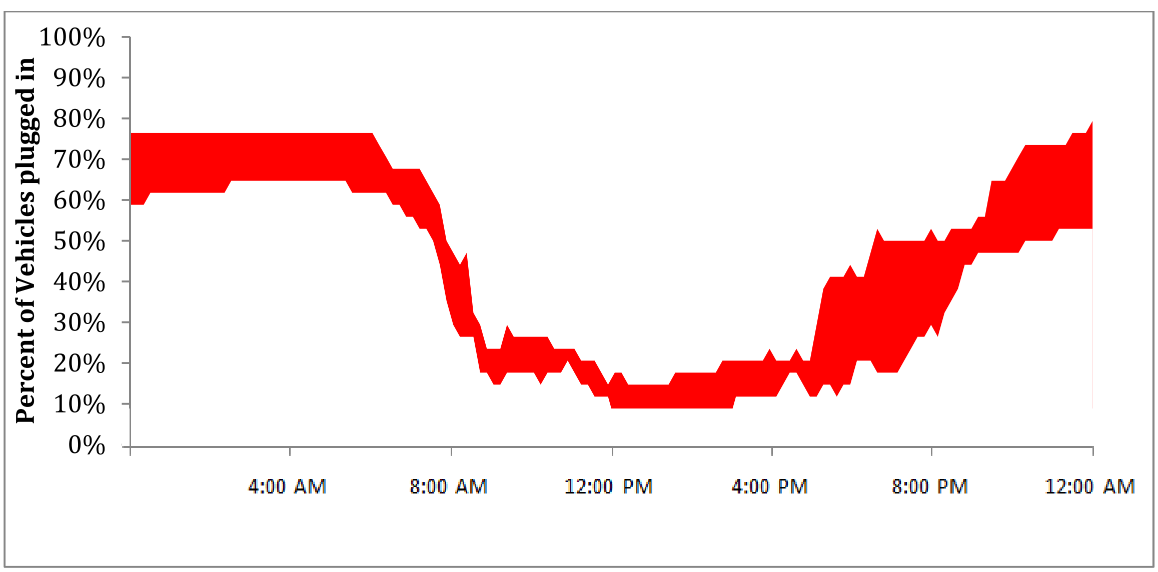


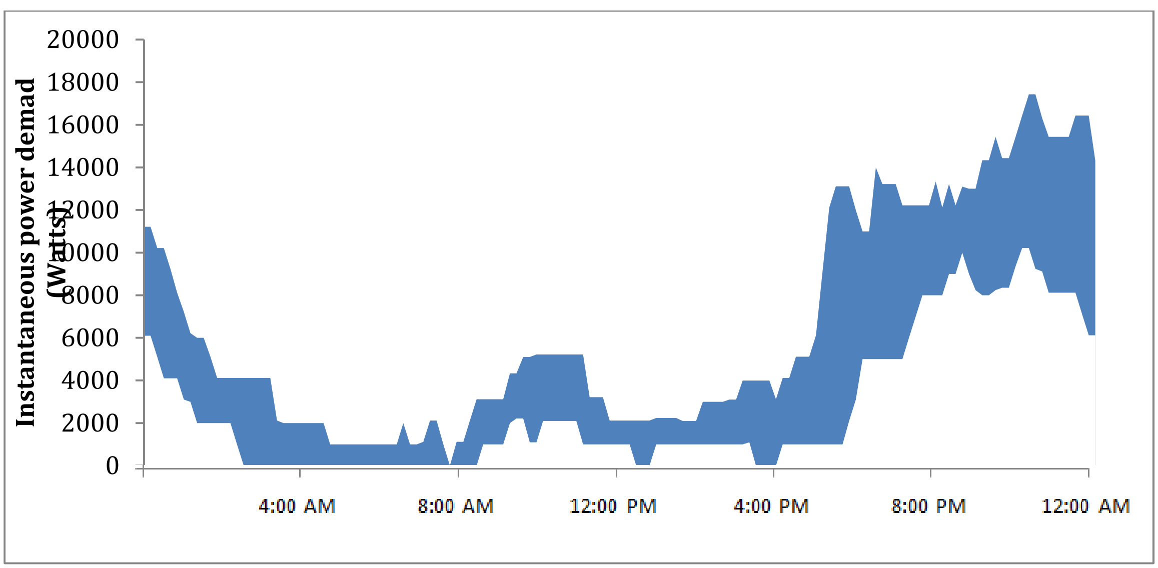
Figure 35: Variability of Weekday Electricity Availability by Time of Day, Percent



As with electricity availability, researchers show the day-to-day variability in instantaneous power demand for a given time of day. For instance, researchers start to disaggregate the average to show the range of demand across weekdays. As Figure 36 shows, the most variability across weekdays in time of day power demand occurs in the evenings between 5:00pm and midnight. The lower boundary of the power demand between 4:00pm and 8:00pm is primarily a result of the increased probability of households plugging in the PHEV later in the evening on Fridays. The upper boundary is shaped by a higher percentage of people charging earlier on Wednesday nights. Regardless of the absolute power level at 5:00pm, there is a rapid increase in the instantaneous power demanded between 5:00pm and 6:00pm.

By comparing electricity availability and instantaneous power demand in Figure 34,researchers see a picture of aggregate charging behavior and, consequently, of grid impacts. In the absence of any signals, prices or supporting systems, households tended to plug in their PHEVs in the early evening, usually upon arriving home, and to unplug them when they left home in the morning. This means that the period between 5:00pm one day and 9:00am the next morning on weekdays is the period with the highest average likeliness of a PHEV being connected to the grid. Instantaneous power demand increases rapidly starting at 5:00pm as more vehicles are plugged to the grid, especially if those vehicles plugged in earlier have not yet finished charging.

Figure 36: High and Low Weekday Instantaneous Power Demand, Watts



While the prospect of rapid increases in electricity demand during peak hours is frightening to electricity providers as well as to energy and environmental analysts, it is clear from project data observations that there is potential to shift electricity demand for these PHEVs from the early evenings, such as, 5:00pm to 8:00pm, until after 10:00pm, since instantaneous power demand to charge these vehicles declines rapidly after 10:00pm and all charging is completed by 5:00am the following morning.

3.4.2.2 Electricity Availability and Instantaneous Power Demand: Weekend Days

Weekdays may provide routines to daily life, including vehicle travel: a daily commute, trips to school or daycare, or the stop at the grocery store before heading home. Weekends may lack these routines or have their own. Driving and charging behavior, access to a plug during the day and the time of day instantaneous power demand, may differ from weekdays. To track and account for these differences, researchers provided an analysis of weekend days that parallels the analysis for weekdays.

Figure 37 shows the average percent of vehicles plugged in at a given time of day during weekends (in red, on the left axis) and instantaneous power summed across households and averaged across weekdays (in blue, on the right). Fewer PHEVs are plugged in during the weekend high availability period than during the weekday high availability period: about 55 percent of vehicles were plugged in between 11:00pm and 6:00am on weekends as compared to 70 percent between 10:00pm and 6:00am weekdays. Note also that the high availability period starts an hour later on weekend days than on weekdays. While electricity availability decreases toward and into the morning, it does so gradually and does not decline below 15 percent. The incidence of vehicles being plugged in again between 2:00pm and midnight increases less rapidly than on weekdays. Compared to weekday charging, it appears as though some individuals, if they had access to an outlet, plugged in longer during the weekend. However, on average, not as many people plugged in their vehicles on weekend days compared to average weekdays.

Figure 37: Electricity Availability (Percent of PHEVs Plugged-in) and Instantaneous Power Demand by Time-of-Day (Watts), Weekend Day Average.

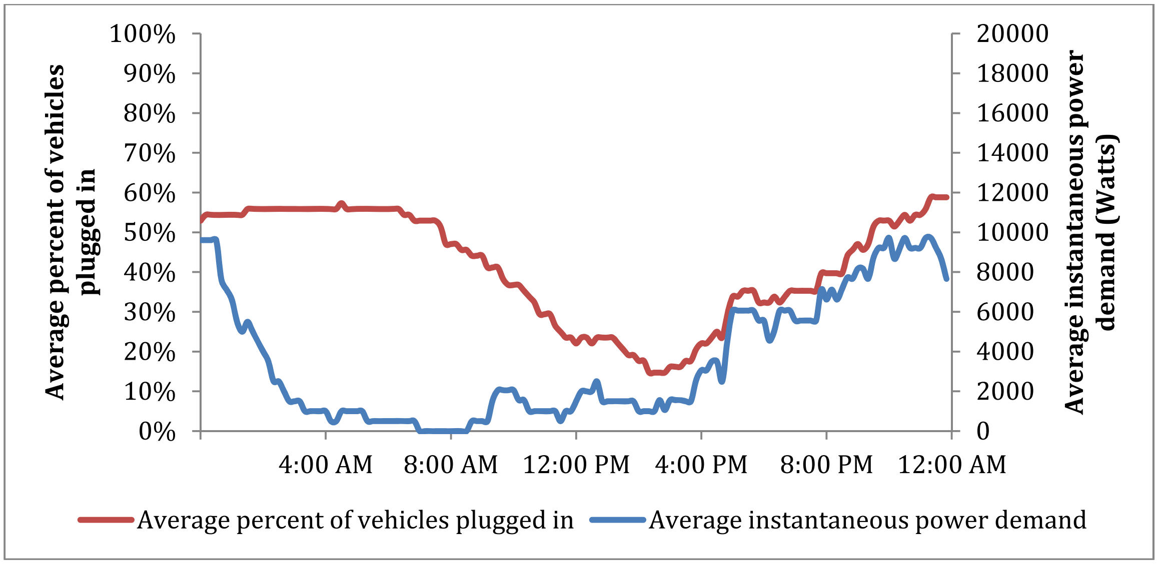


Figure 38 shows the low and high values for the percentage of vehicles plugged in during weekend days. While there appears to be little variability in the percentage of vehicles plugged in during the morning and afternoon, there is a greater difference between 7:00pm and 12:00pm. The lower boundary is made up of those charging events that occurred on a Saturday, with people tending to plug in later in the evening. Sunday charging makes up the upper bound of the evening in the figure, where most vehicles had been plugged in by 8:00pm. The blank areas signify no difference between the high and low values.

Figure 38: High and Low Electricity Availability by Time of Day: All Weekend Days

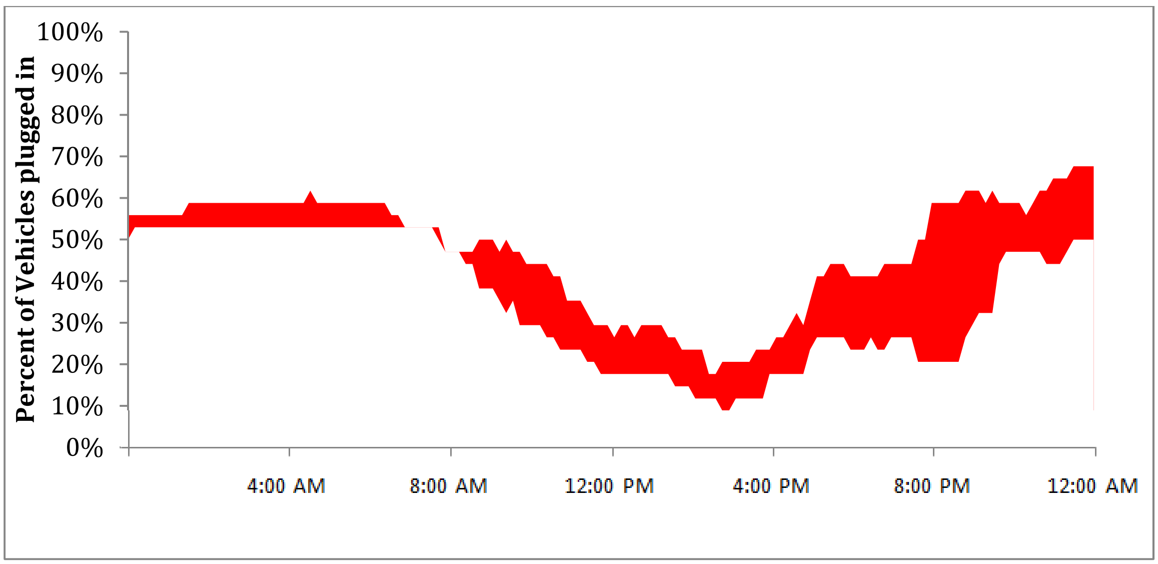


Figure 39: High and Low Weekend Days Instantaneous Power Demand, Watts

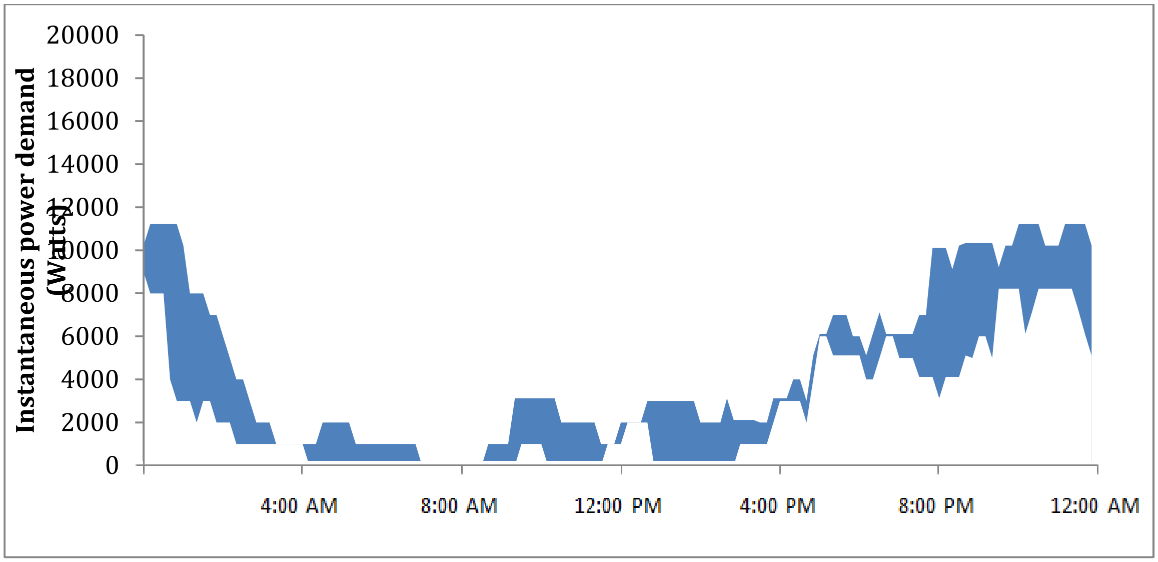


Figure 37 also shows the average instantaneous power demand incurred on all weekend days. As with weekday electricity demand, most actual electricity demand to charge the vehicles occurred between 5:00pm and 2:00am during weekend days. However, it should be noted that there are significant differences in the total power required. On average, weekend electricity demand increased more slowly over the course of the evening. In general, this difference from weekdays is because during weekends the PHEVs are starting their charging at a higher state of charge than on weekdays, and, thus, there is not as great a cumulative impact upon the power demanded. Essentially, as those vehicles plugged in later start charging, their impact on the rate at which total power demand increases (summed across all households) is less than on weekdays, because other households' vehicles which were plugged in earlier have already finished charging.

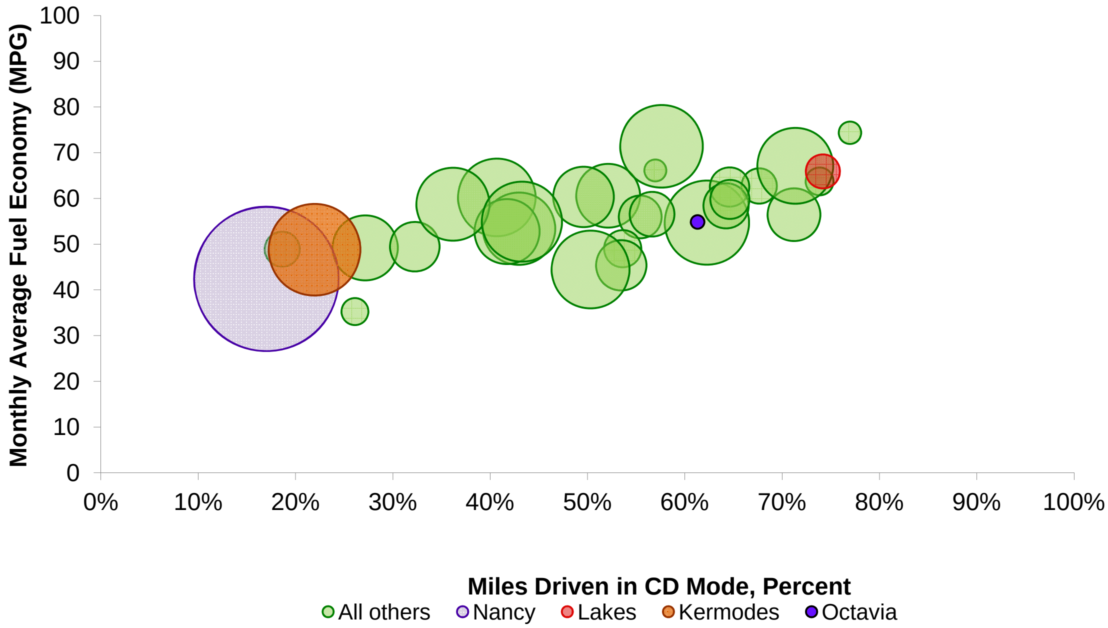
Figure 39 shows the low and high instantaneous electricity demand for all weekend days. Unlike weekdays, the greatest difference is in the very early morning. The upper boundary for the evening electricity demand is due to the demand observed on Saturdays, when people generally charged later than on Sunday. During weekends, the PHEVs were, on average, plugged in until later in the morning, and charging took place over a longer time period and at lower total energy demand during the evening. Since the PHEVs started charging at a higher state of charge and the vehicles were plugged in over a longer period of time, instantaneous electricity demand increases more slowly over the course of the evening than was the case for weekdays. As with the case of weekday instantaneous power demand, it appears as though there is an opportunity to shift charging of these PHEV-conversions by these households to present off-peak electricity demand periods.

3.4.5 Variation in Vehicle Use, Charging, and CD-miles Across Households

The charging results presented so far focus on the charging behavior summed and averaged across the participants. This hides the variation in 1) the frequency with which people charged the PHEV, 2) the distances households drove per charging interval, such as, the distance driven between two charging events, and 3) the percentage of total miles each household drove in CD mode. The participants varied in their experiences with the vehicle, in their concepts and appreciation of the value of charging, and in their access to different charging locations.

Figure 40 illustrates the overall variability in performance of the participants with regard to their average monthly (gasoline-only) fuel economy, the percentage of miles they drove in CD mode, and the overall distance they drove in the PHEV during their respective vehicle trials. In Figure 40, each circle represents one household. The diameters of the circles are proportional to the total miles driven by that household in the PHEV over their trial period. The largest circle (Nancy, in the lower left) represents just over 3,000 miles of driving. That it also depicts the lowest percentage of miles in CD mode and nearly the worst gasoline-only fuel economy in the trial to date is indicative of several long, multi-day tours away from home during which Nancy rarely charged the PHEV-conversion.

Figure 40: Gasoline-Only Fuel Economy by Percentage of Miles Driven in CD Mode, Weighted by Total Monthly PHEV (CD+CS) Distance



The basic conclusions to be drawn are that individuals varied greatly in their driving and charging behaviors and, importantly, in the relationship between these two. A few households drove only 20 to 30 percent of their miles in CD mode—and for their additional use of electricity from the grid achieved overall gasoline-only fuel economy that is barely equal to the EPA fuel economy ratings of a conventional Prius (though, on average, they always outperformed their own driving of the PHEV-conversion in CS operation). On the other hand, a few households drove approximately 80 percent of their miles in CD mode and achieved monthly average gasoline-only fuel economy measures of approximately 70 mpg. A simple linear regression fit to the (distance-weighted) data is statistically better than simply fitting the mean of the mean average fuel economies (at ◎ < 0.01), but returns a modest adjusted R2 = 0.55. The parameter estimated for the change in monthly mean mpg for a one-percentage point increase in the percent of miles driven in CD mode is 0.346: each percentage point increase in miles driven in CD mode leads to, on average, an increase of just over one-third mile per gallon in the monthly average fuel economy. While, as expected, a larger percentage of driving in CD mode is correlated with higher monthly mean fuel economy, there is much about the variation across households which are not accounted for by this simple model.

Figure 40 shows the potential for drivers of these particular PHEV-conversions to achieve reductions in the gasoline-intensity of their daily mobility through changes in how they drive and charge the vehicle, for example, driving and charging such that the miles in a charging interval closely match the driver-vehicle's CD range. Still, there is tremendous variability in how closely participants' behavior matches this technically ideal pattern that is not illustrated in

Figure 40.Researchers explore next the potential for differences in travel and charging behavior to influence measures of gasoline and electricity use, both next through the more detailed examination of one household's fuel economy and CD-mode data, and in an elaboration of three other households' overall experience in the following section on narratives.

3.4.6 The Kermodes

Researchers disaggregate the PHEV driving and charging of one household into their PHEV charging intervals. Researchers chose this particular household not because researchers judge them to be representative of the all the project households or generalizable to all households, but because they illustrate the large effects that differences in travel and charging behavior can make, even within one household. The Kermodes' aggregate gasoline-only fuel economy and CD miles are shown in Figure 40 by the relatively large bubble centered on (22 percent CD miles, 49mpg). This makes them one of the worst performing households on one metric that is obvious and important to the project households: (gasoline-only) fuel economy. Researchers will show however that their aggregate performance masks a wide range of driving and charging behaviors, signals to which the Kermodes responded, and possible summary measures to evaluate what difference it makes to the Kermodes to drive a PHEV versus some other vehicle.

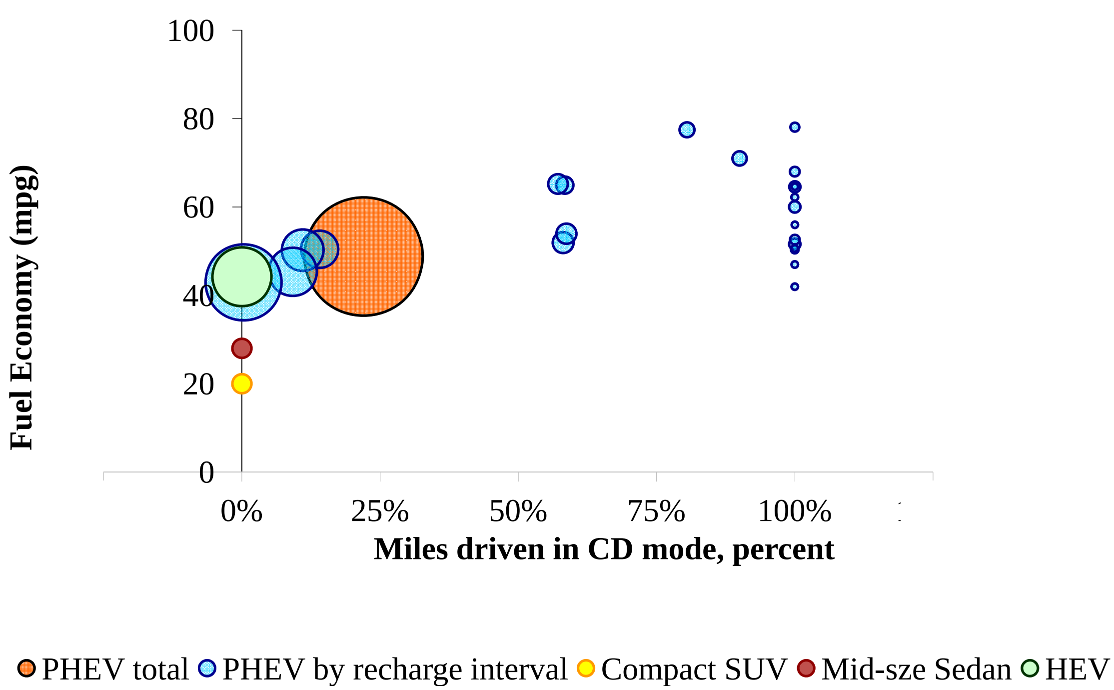
Researchers disaggregated their six-week experience with the PHEV-conversion in Figure 41. While also a bubble chart in which the sizes of most of the bubbles are proportional to miles driven, the bubbles for their existing mid-size sedan and compact SUV are not proportional to distance traveled but are sized only to make them easily perceptible in the figure. The Kermodes' PHEV trial period lasted six weeks. For the first two weeks they drove the car with the PHEV conversion switched off, that is, they drove a slightly overweight but otherwise conventional Prius. During this time, they drove the vehicle 480 miles, averaging 44.2 miles per gallon, and—by definition—their percentage of miles driven in CD mode was zero. The green circle labeled HEV centered at (0 percent, 44.2mpg) in Figure 40 illustrates this performance.

After two weeks, the PHEV conversion was switched in-line and the Kermodes drove the PHEV for four weeks. The aggregate measure of their four weeks driving the PHEV is shown by the large circle labeled PHEV total centered at (22 percent, 49mpg). This large circle is then disaggregated into the small circles (labeled PHEV by charge interval) representing each of the charging intervals that make up their aggregate performance. Each blue bubble identifies a charging interval, that is, a new blue bubble would be added to the figure each time the car is plugged in. For each, researchers plot the gasoline-only fuel economy and the percentage of miles driven in CD mode, sized in proportion to the number of miles driven in that interval. Researchers see that the variety of performances per charging interval within this single household is greater than the variety of the monthly average performance across all the households shown in Figure 40.

For their six-week PHEV trial, the Kermodes most often substituted the PHEV-conversion—whether driven as an HEV or PHEV—for the mid-size sedan Ursula drives on a day-to-day basis. They charged the vehicle at home every evening when they were in-town; when traveling out-of-town on multi-day tours, the vehicle was not charged until their return home.

Differences in their vehicle use and the relationship between their travel and charging behavior explain the three groups of PHEV charging interval bubbles in Figure 41. From left to right, the first group is made up of the four largest bubbles, all representing multi-day tours away from home during which the vehicle was not charged. The only place the Kermodes charged was at home, with a single exception of a brief effort to charge at a family member's home during one of these long tours. For these tours, the PHEV substituted for the household's luxury compact SUV rather than Ursula's sedan. Second is a group of six charge intervals that each represents a single day of driving around the Kermode's home city that exceeds their achieved CD range: the Kermodes were able to drive up to 35 miles in CD mode in their around-town driving. Third is the group of several days during which 100 percent of miles were driven in CD mode—these were all days that Ursula drove the vehicle for her daily commute and errands, as well as for some occasional evening trips.

Figure 41: The Kermodes' Distance-Weighted Gasoline-Only Fuel Economy by Percentage of Miles Driven in CD Mode per Charging Interval



Clearly the Kermodes' driving and charging behaviors and the resulting fuel economy measures differed widely throughout their four weeks of PHEV use. The questions thus arise: how representative are any of the three groups of charging intervals? Or, for that matter how representative is their PHEV trial month as a whole? The long trips the Kermodes took during which they accumulated hundreds of miles without charging are normal trips for them: the Kermodes did not simply set off on several road trips because researchers had given them a free car. In that sense, the entire month is representative of a month of the Kermodes' travel—but not of every month. The Kermodes report the longest trips in their PHEV trial month are made typically twice a year. Based on the measures from the vehicle and the interviews of the Kermodes, an alternative month can be constructed in which the longest trips are replaced by other weekend travel days when the Kermodes stayed home. This constructed month yields new aggregate measures of 885 miles of PHEV travel, of which 48 percent of mile were traveled in CD mode, resulting in an aggregate, gasoline-only fuel economy average of 55 mpg. These two months of PHEV use—one as lived by the Kermodes and recorded by the on-board data systems and the other as constructed from that month based on the Kermodes' interviews—are summarized in Table 7. The Kermodes' lives over the course of a year can be represented by some combination of months like those shown in the table. The majority of months will be closer to the constructed month. But a couple of months a year will look similar to their actual PHEV trial month. The energy and environmental effects further depend on vehicle substitution within their household. In their actual PHEV trial month, the PHEV-conversion substituted for both their compact SUV for long trips and for their mid-size sedan for daily commutes.

It seems plausible then that, at the expense of the additional electricity consumed from the grid, the Kermodes would improve their gasoline-only fuel economy by as little as ten percent and as much as 180 percent depending on what is chosen as the comparative vehicle and travel.[19] Compared to their own vehicles, driving this particular PHEV likely would achieve the claim of PHEV advocates to double your fuel economy. Unfortunately for their claim, advocates have been arguing that the doubling occurs relative to CS operation of a conventional Prius. The Kermodes are achieving nowhere near this increase: across the two months shown in Table 7 they achieve a 10 or 25 percent improvement; even their best single charge interval fuel economy (78mpg) approaches only an 80 percent increase in their CS fuel economy. (During one short all-CD charging interval, they had worse fuel economy than they achieved in CS driving, perhaps illustrating the sensitivity of this specific vehicle-conversion to the effects of cold starts and the operation of the emissions system for the ICE.)

The point here is not that advocates are wrong or that these PHEVs under-perform (or over-promise). Clearly, there is some PHEV in which the Kermodes could double their CS fuel economy while in CD mode. The point is that the efficacy of PHEVs is sensitive to not only technical design, but also driving and charging behaviors and reference cases.

3.5 Overall Effects of Charging on Energy Use

One measure of the effects of charging is the difference in (gasoline-only) fuel economy. Researchers describe these results first as it is the measure used by most participants. Across the group, the mean CS fuel economy was 44.7mpg; the mean CD fuel economy was 67.1mpg. Thus, the group mean increase in CD versus CS is 49 percent. These group measures mask tremendous variation across households. The distribution of households' mean fuel economy

[19] As Ursula Kermode approaches retiring, they have already discussed reducing their vehicle holdings to one car. It is our judgment based on the interviews, that it is most likely they would keep the newer, more luxurious, but less fuel-economical, compact SUV.

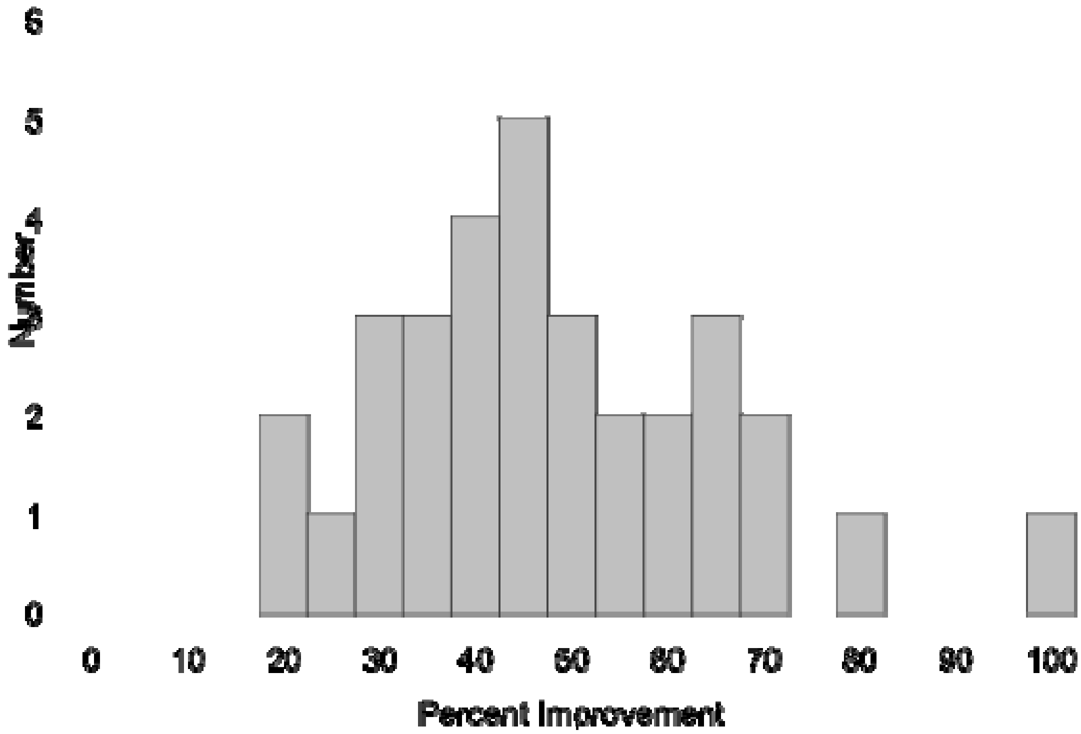
improvements between CS and CD operation is shown in Figure 42. The range is from 21 to 101 percent. However, improvements over 70 percent are exceptions—90 percent of households had improvements less than 71 percent and the median improvement was 46 percent.

Table 7: Aggregate Measures of the Kermodes' Actual and Constructed Months of PHEV Driving and Charging

	Month	
	Actual PHEV	Constructed[1]
Miles	1,932	983
Percent miles in CD	22	48
Mean Monthly Gasoline-only Fuel Economy, mpg	49	56
Percent Difference from Kermodes' mid-size sedan[2]	74	100
Percent Difference from Kermodes' compact SUV[3]	144	180
Percent Difference from Kermodes' non-PHEV Prius[4]	10	27

1. The constructed month is based on the actual month, but substitutes measures of the Kermodes' travel for weekends they remained home for a multi-day tour they made over one long weekend.
2. The Kermodes estimated the fuel economy of their mid-size sedan to be 28mpg.
3. The Kermodes estimated the fuel economy of their compact SUV to be 20mpg.
4. Driving the PHEV-conversion for two weeks in CS operation, such as, with the PHEV conversion taken off-line, the Kermodes achieved an average of 44mpg. This period included one weekend trip out of town.

Figure 42: Improvement in Gasoline-Only Fuel Economy rom CS to CD Operation



Another measure that begins to integrate vehicle performance capabilities with owners' driving and charging behaviors is the percent of miles driven in CD mode. As the vehicle is fixed in this project, differences across households are due to driving and charging behaviors. The discussion above of (gasoline-only) miles per gallon reflects the use of this measure by most households as the goal and measure of their experience with the vehicle (though fuel economy was translated into other goals by different households, for example, cost reduction and environmental benefit). A few households used other measures related to gasoline use, for example, distance, cost per tank, or frequency of gasoline refueling. No household created for themselves an integrated assessment of both their gasoline and electricity use.

Such an integrated analysis is essential to the question of whether PHEVs deserve societal sanctions. The analysis presented here is preliminary and partial. It is preliminary because researchers do not expect that the full range and variety of the relationships between travel and charging behavior on one hand and total energy use on the other have yet been observed among the project participants' to date. Further, this analysis is preliminary because only one particular PHEV is analyzed. The analysis is partial because it is not a life-cycle analysis; here researchers address only electricity out of the battery and gasoline out of the tank. Further, the analysis is partial because researchers address only the marginal difference that it makes that the project households drove (and charged, to the extent each did) a PHEV instead of an HEV.

That is researchers compare their actual total energy use, such as, gasoline plus electricity, during their PHEV trial to the amount of gasoline they would have used had they driven their entire PHEV trial without every charging, such as, entirely in CS operation. To illustrate relationships between driving, charging, and energy use researchers plot the marginal percentage decrease in total gasoline (tank to wheels) plus electricity (battery to wheels) by the percent of their miles they drove in CD mode for their four-week PHEV trial in Figure 27.

The first point is that a comparison of Figures 40 and 43 shows that the households' use of the simple measure of (gasoline-only) fuel economy is not qualitatively wrong. As the percent of miles driven in CD mode increases, fuel economy and total energy savings both increase. Whatever additional (dis)motivation, travel, or charging would have resulted if households had created integrated representations of gasoline plus electricity use, cost, and emissions, the use of a simple measure of gasoline-intensity of their travel did not produce counter-productive outcomes. Figure 43 confirms that across the households, energy was being saved through the substitution of electricity for gasoline by charging the PHEVs compared to what these households would have consumed had they not charged the PHEVs—a conclusion that cannot be reached from Figure 40.[20]

The four households we've discussed in more detail are situated similarly in both figures. The relatively low percentage of CD driving of Nancy and the Kermodes—which researchers know was due to long, multi-day tours during which they did not charge the PHEV—yields low percentage energy savings from a large (compared to the other households) base. Octavia and the Lakes achieved much higher percent energy reductions but across much less travel, and thus a smaller energy base. They did so in part because of the much higher percentage of their travel they accomplished in CD mode—accomplished both because they charged more often and traveled fewer miles than Nancy and the Kermodes.

The four households in the furthest upper-right of Figure 43 provide interesting contrasts illustrating that driving fewer miles isn't the only strategy to high percentage energy savings. The data for these four households are provided in the first four rows of Table 8. Two of the households drove only 500 to 600 miles during their four-weeks driving the PHEV—about three-fourths of these miles in CD mode. They achieved total energy savings of 19 and 18 percent compared to what they would have achieved had they never charged. Because they traveled short total distances, they each displaced three to four gallons of gasoline, in part by consuming 56 to 64 KWh of electricity (out the battery).

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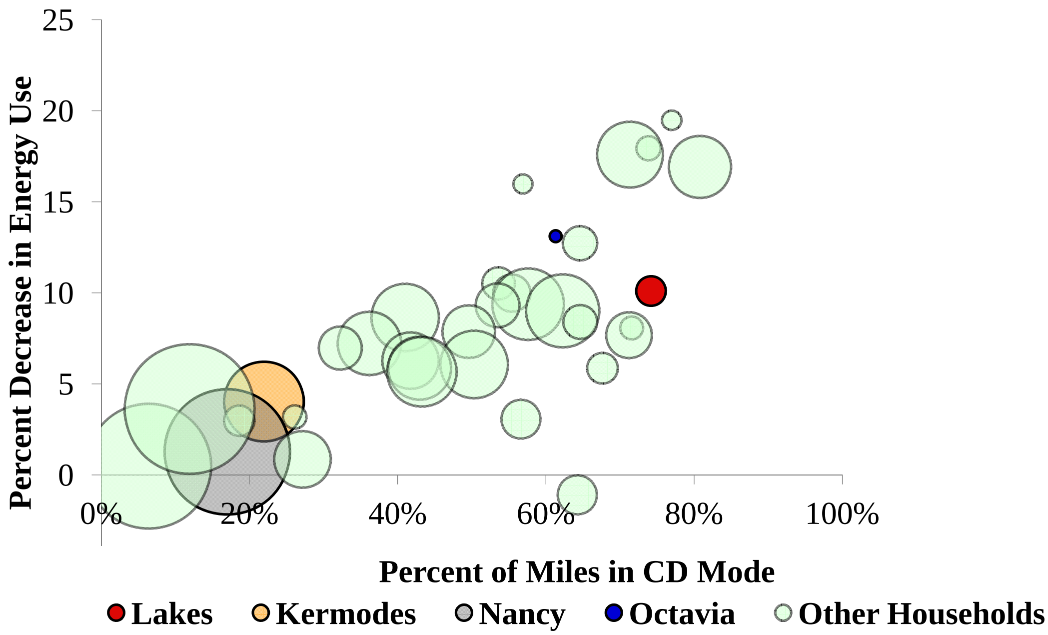
[20] The household that shows an actual increase in energy use, such as, a negative percentage decrease, despite a high percentage of miles driven in CD, had drivers with different driving styles and distances per trip. That is, one driver's average CS fuel economy was as good as or better than the other driver's CD fuel economy.

Figure 43: Decrease in Households' Total Energy (Gasoline Plus Electricity) for Their PHEV-Conversion (as Compared to an HEV) by Percent of Miles Driven in CD Mode, Percent



In contrast, the other two households who achieved the highest percentage energy savings—17 and 18 percent—drove over 1,500 miles during their PHEV trials. Their proportion of miles driven in CD mode is high: 71 to 81 percent. These two households each displaced nine to ten gallons of gasoline, in part by consuming about 141 KWh of electricity. How did these two households achieve similar percentage energy savings over many more miles than the previous two? The households that traveled longer distances achieved high percentages of CD mode by charging multiple times per day. Both these households had one-way commutes that were about the distance of their realized CD range and both charged at both home and work. In a sense, these two households achieved double (or more) their effective CD range daily; the households who traveled shorter distances but achieved similar percent savings did so because so many of their travel days were shorter than their realized CD range.

The effects of the adaptations to a PHEV within a household can again be illustrated by the case of the Kermodes. Substituting the month researchers have constructed to simulate a month during which they do not take their long trips to southern California, but stay in-town, their percent total energy displaced increases from the four percent calculated for their actual month to 14 percent.

In aggregate across all the first households to participate in the project, each driving the same version of a PHEV for four weeks, they drove over 33,000 miles. In doing so, and in charging the PHEVs, they displaced 110 gallons of gasoline, at the expense of 2,066 KWh of electricity.

Each of the households displaced as little as one gallon of gasoline to as much as almost ten, at the cost of 19 to 141KWh respectively. A simple regression across all households returns an adjusted R2 = 0.86 and an estimate that for each kilowatt-hour (out of the battery), on average, these households driving and charging these PHEV-conversions displaced 0.065 gallons of gasoline, out of the tank, compared to the amount of gasoline they would have consumed had they not charged.

Table 8: Energy Use and Savings, Sorted by Percent Decrease in Total PHEV Energy Use

Name	Total VMT	Percent Miles in CD	Gasoline Displaced (Gallons)	Electricity (KWh)	Δ Total Energy (KWh)	Percent decrease in Total
	471	77%	3.43	55.85	69.60	19%
	587	74%	4.13	63.60	87.65	18%
	1,598	71%	9.76	141.08	216.20	18%
	1,505	81%	8.93	141.30	185.92	17%
Octavia	286	61%	1.58	25.16	32.62	13%
	830	65%	4.35	77.10	82.14	13%
Lake	716	74%	3.64	79.68	53.64	10%
	902	55%	3.78	65.73	72.83	10%
	1,739	58%	6.81	91.58	157.71	9%
	1,772	62%	6.37	105.41	127.91	9%
	824	65%	3.41	71.87	52.87	8%
	1,275	50%	4.27	83.04	73.23	8%
	1,111	71%	4.37	92.61	67.61	8%
	1,538	36%	4.56	85.76	81.36	7%
	1,043	32%	3.06	50.40	61.66	7%
	1,369	42%	3.56	62.61	67.82	6%
	1,639	50%	4.52	89.22	76.36	6%
	743	68%	3.17	83.90	32.23	6%
	1,526	43%	4.06	78.66	70.05	6%
	1,687	43%	4.20	73.70	80.26	6%
Kermode	1,932	22%	3.33	58.57	63.32	4%
	568	26%	1.21	24.08	20.18	3%
	944	57%	2.54	71.38	21.58	3%
	738	19%	1.09	18.79	21.18	3%
Nancy	3,040	17%	2.77	67.08	34.55	1%
	1,372	27%	1.38	41.20	9.17	1%
Total	**33,422**	49%	**110.10**	**2,066.40**	**1,965.91**	

CHAPTER 4:
Conclusions and Discussion

4.1 National Survey of New Car Buyers

Results from the national survey offer initial answers to questions regarding consumer awareness, charge potential, PHEV design priorities, and energy impacts in an early PHEV market. In regards to the last three, researchers' simulated world contains greater variety of PHEV designs than any prior study. This is an intentional difference, allowing respondents to design the PHEV they would most desire given their current understanding and valuation of four PHEV performance parameters. Researchers believe this is a more realistic representation of a plausible near future than the imposition of one or a few PHEV designs on the entire population of vehicle drivers.

Researchers' scenario analyses remain susceptible to other threats endemic to such efforts. Radically changing travel behavior, in response to fuel prices, competition from other alternatives, or in response to PHEVs themselves, could invalidate the use of data on existing real travel. Rapid technology development and cost reduction—or their delay, may render the design games under-, or over-optimistic. None of them are likely to capture precisely what will happen with workplace charging, efforts to control time of day of charging, or efforts to provide home charging to the one-third to nearly one-half of new car-buying households who do not now find that where they park their cars at home has access to electricity.

4.1.1 Awareness of Electric Drive Vehicles

While acknowledging that vehicle buyers generally do not need intimate technological understanding of a given vehicle to ensure purchase, researchers do suspect that basic levels of awareness and understanding can play an important role in the introduction of a vehicle that operates in a fundamentally new way and provides symbolic meanings not previously available from motor vehicles. Responses to this survey suggest that presently the majority of new vehicle buyers have little or no familiarity with the idea of a PHEV, and may erroneously believe that existing hybrid-electric vehicles can perform the same basic function of a PHEV, such as, have the ability to be refueled by gasoline and to be plugged into an electrical outlet. The latter finding is particularly surprising, given that HEVs have been available in the U.S. auto market for almost a decade. These perceptions of HEVs indicate there is both potential for misconceptions and confusion regarding the availability and purported benefits of PHEVs and that such misconceptions may persist for years. Potentially related to this is the further finding that respondents did not exhibit a strong attraction to all-electric operation in CD mode for PHEVs. Given that the vast majority of respondents have not experienced electric drive vehicles, they may have limited understanding of potential benefits including functional attributes such as reduced noise, vibration, emissions, and costs, as well as the personal and shared meanings that have come to be associated with HEVs (Heffner, 2007 and Heffner et al 2007).

This lack of awareness and understanding is both a constraint and opportunity. As a constraint, unaware consumers may simply fail to recognize or identify compelling benefits of owning and operating a PHEV, serving as a soft constraint to limit the market. On the other hand, the early PHEV market in the U.S. may be seen as a blank slate, with little preexisting understanding of what a PHEV is or expectations of what it should be. Thus, the early actions of automakers, governments, electric utilities, and other stakeholders could play an important role in establishing perceptions in the market. For example, despite the initial lack of PHEV awareness among the sample, once respondents were provided with basic descriptions of the technology (in the Plug-in Buyers' Guide provide to them as part of their survey), the majority expressed interest during the design exercises. Similarly, the first commercially available PHEV incarnations could set an early bar for consumer understanding and set expectations of performance levels.

4.1.2 Charge Potential and Timing

Based on the results reported here, researchers conclude that just more than half the population of households that buy new cars has the potential to charge a vehicle at home with at least 110-volt service. This estimate is one-and-a-half to three times larger than previous estimates of home charging potential in the entire population of American households by Nesbitt et al (1992) and Williams and Kurani (2006). The reasons for this difference are that the present analysis (1) targets new vehicle buying households rather than general population of American households, and (2) draws information directly from the respondent's identification of charge opportunities instead of relying on proxies from U.S. Census or other data. Given their own observed driving and parking behavior, few drivers perceive an opportunity for non-home charging opportunities, such as at their workplace, friend's and family's homes, restaurants, and so forth. Therefore, researchers selected access to home charging as a key constraint for what researchers call the higher home charge potential segment. Within this segment researchers find that although a higher proportion of respondents with single-family dwellings found home charge opportunities than respondents in other housing types (attached, apartments or mobile homes), this condition is neither necessary nor sufficient for charge potential. Researchers find a similar pattern for respondents who typically park their vehicle in a private garage at home.

As previously assumed and reported, for example, by Lemoine et al (2008), Duvall et al (2007), Samaras and Meisterling (2008), and Hadley and Tsvetkova (2008), vehicle access to charge infrastructure as identified by diary respondents follows an inverse of the diurnal pattern of driving activity. Charge potential, that is, the spatial-temporal correspondence between a parked vehicle and a 110-volt electrical outlet, peaks between 12am and 6am when most vehicles are parked at home and reaches a broad minimum from 10am to 4pm when most vehicles are parked at work or other locations or being driven.

The present analysis is useful in providing a plausible baseline for the early PHEV market; but a baseline from which consumers, infrastructure and vehicle providers, and policy makers can create change. Research suggests that with the right incentives, consumers might locate more charge locations, modify existing charge locations, for example clean up the home garage, and adjust driving patterns and adapt vehicle use among the household fleet to maximize electricity use (Kurani et al, 1996, 2007). Much adaptation by consumers may not occur until after they purchase a PHEV, and their perceived charge potential that may lead to PHEV purchase may be based on existing driving patterns, such as, current perceptions of charge locations.

Still, it may be possible to lead PHEV purchases by changing perceptions of the availability of vehicle charging, by actually increasing the availability of charging for those households who do not now find it and by improving the visibility and viability of existing electrical infrastructure for vehicle charging. Charge infrastructure could expand to a higher percentage of households with changes in building codes, as well as increased employer and publicly installed vehicle charge outlets.

4.1.3 Design Priorities

Among the respondents with at-home vehicle charging, most constructed more expensive vehicle designs that added plug-in capability to their next vehicle purchase than did those without access to charging. Given access to charging and the distribution of PHEV designs from the games, researchers estimate that about one-third of U.S. new vehicle buying households have both the required infrastructure and interest to purchase a vehicle with plug-in capabilities. The variety of PHEV designs created by respondents suggests there is still ample opportunity for automakers to explore and develop different PHEV designs.

Researchers observed a wide diversity of consumer interests in PHEV design options. Starting with a base PHEV design offering long charge times, short CD range, no all-electric operation, but non-trivial increases in both CD and CS gasoline fuel economy, the most popular upgrade category was to further improve fuel economy in CS mode. Respondents also exhibited interest in increasing vehicle range in CD mode, and improving CD fuel economy. Fewer respondents were willing to devote resources to reduce charge time; most potential early market respondents have access to periods of home-based charging long enough to fully charge each day even at the slowest offered rate.

Researchers found little evidence of inherent demand for all-electric operation in CD mode, even following the one day diary, the tutorial on electric-drive vehicles, and PHEV design games. An even smaller subset was interested in creating a vehicle with performance attributes including 40 miles of all electric CD range. These patterns contrast with the findings of Kurani et al's (2007) interviews with pioneer PHEV conversion drivers who exhibited strong interest in maximizing CD range in all-electric mode—effectively to approach the capabilities of pure electric vehicles. This difference suggests that while all-electric CD operation may be particularly attractive to a small subset of consumers, including those who are already knowledgeable and experienced with electric vehicles, at this point in time most households who buy new vehicles are more interested in high fuel economy.

Also, about one-third of the potential early market respondents who constructed a PHEV variant of their likely next new car (that they selected rather than a conventional version of that car) chose no upgrades above the proffered base PHEV design. Overall, there may be substantial potential for market success with less ambitious PHEV designs, such as blended operation with shorter CD range but high CS fuel economy. This wide variety of PHEV design selections further supports the notion of a blank slate early PHEV market, where early buyers may have little in the way of performance expectations.

Desired PHEV designs and capabilities may be subject to change. Survey respondents had little pre-existing understanding of PHEVs and the responses researchers elicited may be sensitive to the PHEV information researchers provided. As information about PHEV technology, costs, benefits, and meanings are transmitted throughout the population, interest in particular attributes and performances could shift. For example, all-electric CD operation could become more meaningful to car buyers as they gain experience and as they participate in the process of identifying just what all-electric operation means to people. In the meantime, this analysis provides a baseline of market potential—one that could be subject to influence. The messages and actions of policymakers, automakers, electric utilities and other interest groups could have significant influence over future development of awareness, charge potential, design interests, and energy impacts of the PHEV market.

4.1.4 Energy Impacts

The final analysis in this report combined all of the available information from each respondent, driving, charge potential, and PHEV design priorities, to estimate the energy impacts of the respondents existing travel and understandings of PHEVs under a variety of charging scenarios. Results suggest that the use of PHEV vehicles could halve gasoline use relative to conventional vehicles, the majority of this reduction being due to increases in CS fuel economy. Using three scenarios to represent potential boundary conditions on PHEV driver charge patterns (unconstrained, universal workplace charging, and off-peak only charging), researchers estimate tradeoffs between the magnitude and timing of PHEV electricity use. In the unconstrained Plug and Play charge scenario, charging peaks at 6:00pm, following a far more dispersed pattern throughout the earlier part of the day than anticipated by Lemoine et al (2008) and Hadley and Tsvetkova (2008). The more dispersed time-of-day charging pattern in this work is due to researchers' ability to realistically account for heterogeneity in driving and parking behavior and to allow for heterogeneity of PHEV designs. PHEV electricity use could be increased through policies increasing non-home charge opportunities (for example, the Enhanced Worker Charge Access scenario), but most of this increase occurs during daytime hours and could contribute to peak demand (depending on a given region's definition of peak). Researchers also demonstrate how deferring all charging to off-peak hours (8pm-6am) could eliminate all additions to daytime electricity demand from PHEVs, similar to what Lemoine et al (2008) call optimal charging. However, as also found by Kurani et al (1997) for EVs, in this scenario less electricity is used due to the elimination of daytime charge opportunities and less gasoline is displaced.

This analysis provides one measure of the potential threat and opportunity for electric utilities. The threat is that without control, the majority of charging may occur during peak hours (6am-8pm), with a peak at 6pm during weekdays. This spike coincides with seasonal peak electricity demand periods in some U.S. states and with a large enough PHEV market, overall electricity generation requirements may be increased (Lemoine et al, 2008). However, the observed 12am-6am charge potential in late evening and early morning presents an opportunity for smart charging strategies in which PHEV charging (as well as any other electrical load) can be shifted to off-peak periods subject to varying levels of control by electricity users and suppliers.

4.2 PHEV Demonstration, Market Research Project and New Car-Buyers in California

The national survey described in Chapter 2 also contained oversamples of new car buyers in California and in communities along Interstate-80 in California—the region that contains the households who participated in the PHEV demonstration project. Comparisons of all three groups PHEV designs will be made and put into context with the national survey sample. The discussion of charging and energy effects will be limited to the project households.

4.2.1 Comparing the Survey and Demonstration Samples

Almost all socio-economic and demographic differences between the project households (measured as a group) and the general population and the sample of new-car buying households flow from this initial charging capability condition. The project participants are skewed toward people with higher incomes and education—even compared to the California and northern California over-samples. Respondents in all three of the CA-based samples are much more likely to be between the ages of 35 and 54 than the general population. The project and survey respondents are more likely to live in detached homes than are the general population. The present gender balance of the project participants is similar to that of the general US, California, and California over-sample of new car buying households.

Other than these general correlations between income, education, home ownership, and new vehicle buying, the project households cannot be considered to be so pro-PHEV, pro-electric-drive technology, or pro-environmental compared to other samples of new car buyers as to skew their reports in favor of PHEVs. The project sample contains a slightly higher percentage of people who state that air quality, climate change and oil dependence are serious problem[s], and immediate action is necessary than in the California and northern California over-samples. Still the differences are small and researchers judge them to be unlikely to make a substantive difference to any conclusions researchers may draw between the samples on PHEV designs created by participants in their design games.

There is little to distinguish the knowledge of electric drive vehicles of the project participants from the survey respondents—except on the specific issue of plug-in hybrids. Across all samples, very high percentages of respondents know that a plug-in hybrid can be both fueled and plugged-in; the highest percentage is among the project participants. There are a few opportunities for information leaks about PHEVs to respondents in the present project: the recruiting phone call and the information unavoidably provided to households when the PHEV is first delivered. (The questions about electric-drive knowledge are part of a longer, more substantive questionnaire that cannot be administered until after the household is fully enrolled in the project, which occurs when the vehicle is delivered.)

Most project participants faced lower gasoline prices during their PHEV trial month than did the prior survey respondents. However, the first project participants were paying well in excess of $4.00 per gallon for gasoline in August 2008. Whether they faced higher gasoline prices during their PHEV trial period or whether they simply recall such higher prices from last summer, researchers expect that all other project participants may be more sensitive to the uncertainty of gasoline prices than the national and California survey respondents. This may make project participants less like prior survey respondents, but more like their peers, such as, all present day car-buying households who have lived through this same history of gasoline prices.

4.3 PHEV Design Conclusions

4.3.1 Designs That Emphasize Fuel Economy or All-Electric Driving?

The variety of PHEV designs created by survey respondents in California and northern California and project participants suggests there is still an opportunity for automakers to explore and develop different PHEV designs. Researchers found little evidence of inherent demand for all-electric operation in CD mode, even among project participants who had experience driving a (CD blended-operation) PHEV for a month—though project cannot presently exclude the possibility of participants anchoring on what researchers have now made familiar to them, such as, blended rather than all-electric CD operation. An even smaller subset was interested in creating a vehicle with performance attributes combining 40 miles of CD range with all-electric CD operation.

These patterns contrast with the findings of Kurani et al.'s (2007) interviews with pioneer PHEV conversion drivers who exhibited strong interest in maximizing CD range and moving toward all-electric operation—effectively to approach the capabilities of pure electric vehicles. This difference suggests that while all-electric CD operation may be particularly attractive to a small subset of consumers, including those who already have extensive knowledge and experience with electric vehicles, at this point in time most households who buy new vehicles are more interested in high fuel economy, even after completing a multi-week trial with one PHEV incarnation.

The project participants' PHEV designs support researchers' prior conclusion from the national survey that consumers create PHEV designs that emphasize (gasoline-only) fuel economy and, conversely find no evidence to contradict researchers' prior finding of low demand at present for PHEVs offering all-electric operation in CD mode. Most respondents in both studies and across both design games designed PHEVs based on blended operation in CD mode. In effect, they designed PHEVs that emphasized improvements in (gasoline-only) fuel economy over designs that emphasized all-electric driving.

4.3.2 Project Results Differ From Survey Results in Some Important Ways

Project participants who had driven a (blended-operation) PHEV for a month were more likely than the previous survey respondents to 1) design a PHEV they are interested to buy rather than opt to buy a conventional vehicle, 2) design a PHEV that had better PHEV performance than the base PHEV design offered to them, and 3) to choose an HEV as the base vehicle they considered for redesign as a PHEV. Still, these differences are at the margin, and the overall conclusions one draws from the project participants are similar to those researchers drew from the survey. The project does appear to have a slightly greater persuasive effect of convincing participants that a PHEV is a worthwhile and desirable vehicle for their household, as well as an effect of convincing them that an HEV is a worthwhile vehicle for their household. Given that they have designed a PHEV they want, few project participants were interested in faster charging times than the base offering of eight hours—recall, all these households were selected to participate in the project in part because they can charge a vehicle at home. Project participants are more likely than survey respondents to improve CD mode—both operating mode and range. Yet as noted above, the slightly higher prevalence of all-electric designs compared to previous survey samples (~five percent in the project compared to ~one percent in the survey) does not overrule the larger conclusion that only a small minority of new car buyers presently value all-electric PHEV designs. There is little difference between samples in the probability to improve CS fuel economy performance, in large part because this is the most common attribute to be improved by respondents in all samples.

Participation in the project appears to have decreased the importance of improvements in charging rates compared to prior survey respondents, but project participants were selected in part because they are able to charge at home. Project participants were somewhat more likely to design a PHEV for their next new vehicle, rather than revert to a conventional vehicle, than were the survey respondents. Project participants were also more likely to choose a HEV as their base new vehicle from which to consider the design of a PHEV.

4.3.1.1 Where Do Consumers' PHEV Designs Lead?

The wide variety of PHEV designs created by survey respondents and project participants support the notion of a blank slate early PHEV market, where early buyers may have little in the way of PHEV performance expectations. That is, not only is there room for a variety of technical pathways, but also there is room for multiple meanings of PHEVs. Desired PHEV designs and capabilities may be subject to change. Project participants and survey respondents had little pre-existing understanding of PHEVs and the responses researchers elicited are sensitive to the PHEV information and experience researchers did provide. As information about PHEV technology, costs, benefits, and meanings are transmitted throughout the population, interest in particular PHEV attributes and performances could shift too. For example, all-electric CD operation could become more meaningful to, and valued by, car buyers as they gain experience with all-electric driving and as they participate in the process of identifying just what all-electric operation means to people.

The respondents' PHEV designs suggest the possibility of a trajectory over time as the PHEV and electric-drive market develops. The respondents are designing PHEVs that are far more technologically and financially feasible than experts assume. In particular, most of those designs provide some all-electric driving, as even PHEVs that use blended operation in CD mode afford some all-electric driving. If researchers start with these less aggressively electric designs, then over subsequent market and vehicle generations, the electric capabilities of PHEVs can be increased as costs come down, due to learning by doing, technology development, and improved design—as consumers learn to value increased electric-drive capabilities.

4.4 Mediating Behaviors Between PHEV Designs and Environmental and Social Goals: Charging and Driving

4.4.1 Charging Behaviors

The households in this project were selected in part because of their capability to charge a PHEV at home. Further, they are all driving one specific incarnation of what a PHEV can be. For these reasons, and because of the probable correlations between PHEV performance capabilities and driving and charging behaviors, the specific numerical results of this section should be interpreted with appropriate caution.

That said, the households participating in this project are, on average, plugging-in these PHEV conversions about once per day, and do so more often on weekdays than weekend days. There is large variation though even in the means across households—from zero to 2.6 times per weekday and zero to 1.5 times per weekend day. The higher frequency of plugging-in on weekdays is associated with 1) some incidence of charging at work on weekdays and 2) charging at home during the day by retired households. Overall frequency of plugging-in on weekend days is lower not only because there is no workplace charging taking place, but because the PHEVs are more likely to be away from home, and thus the primary or sole charging location.

Comparing electricity availability and instantaneous power demand provides a picture of aggregate charging behavior and potential for electricity grid impacts for weekdays and weekend days, illustrating both when these vehicles could have been charged and when charging actually occurred. In general, most households plugged in their vehicles after 4:00pm on weekdays and left them plugged in until 6:00am. While the electricity demand from vehicles being plugged in between 5:00 and 6:00pm creates a rapid increase in grid electricity demand, the differences between the availability and demand curves show there is opportunity to shift charging to presently existing off-peak electricity demand periods. Compared to weekdays, weekends present even greater opportunity to time-shift grid power for the vehicles since 1) fewer are plugged in, 2) those that are plugged in require less electricity to fully charge, and 3) those that are plugged in tend to remain plugged in longer into the next morning. Furthermore, there are differences in opportunities to use PHEVs as sinks for excess electricity, based on the differences in how many vehicles are plugged in between weekdays and weekend days.

While the electricity availability and instantaneous power demand characterized by this report are representations of what happened across the project households' PHEV trials, it is important to emphasize that individual household charging behavior, vehicle use, and vehicle performance varied across days, charging intervals, and trips. Essentially, while researchers have accurately represented households' last week or month of driving the PHEV-conversion, that record of actual driving during the PHEV trial may not have been representative of every week or month of a household's life. In an effort to demonstrate the different ways households could plausibly use these vehicles, researchers disaggregated the real month PHEV trial of the Kermode family and offered an alternate month based on their interview and vehicle data. The two months—the month as measured including multiple, away-from-home weekend tours and a constructed month that substitutes local weekend travel for the longest of these tours—

provide descriptions within which most of the Kermodes' vehicle driving and charging will fall. Depending on which month and which comparative vehicle(s) one references, the effect on the gasoline-intensity of the Kermodes' travel is bounded by estimates of ten to 180 percent. Further, the marginal effect of charging on their total energy displaced by driving and charging the PHEV ranges from four percent in their actual month of using the PHEV to 14 percent in a month plausibly constructed to represent other months of their life (keeping in mind their actual month with the PHEV does represent some months of their lives).

4.4.2 Driving Behaviors

Researchers treated driving behaviors at two scales. First, daily-to-monthly measures such as the households' percent of miles driven in CD mode summarized the relationship between households driving and charging behavior. Second, a shorter time scale—within a single trip—explored how the vehicle and information interfaces may have changed how people drove.

4.4.3 Summary Measures of Driving and Charging

As discussed in the opening of this report, the potential energy and environmental effects of PHEVs flow from the amount of electricity that displaces gasoline. This in turn depends on the relationship between PHEV designs and capabilities on the one hand, and PHEV drivers' driving and charging behaviors on the other. The percentage of miles driven in CD mode is one measure of how all three interact.

One way to measure the performance of a particular technical specification for a PHEV is to recast it in terms of the realized performance based on our participants' driving and charging behaviors. In this way the vehicle used in this project can be described as follows (with the range of observed measures in parentheses):

1. A PHEV that operates in blended mode during CD operation;
2. During which it will return (21 to 101) percent better gasoline-only fuel economy than it otherwise achieves in CS operation;
3. CD operation will last for (25 to 35) miles using a definition of CD range that references only the switch from CD to CS operation;
4. In exchange for about 4KWh of grid-electricity; and,
5. Achieves (38.0 to 51.5mpg) in CS operation (where percent improvement in CD operation is positively correlated with CS fuel economy across drivers).

The ranges of CD and CS performance values above are explained in part by differences in aggressiveness of accelerations, top speeds, mixes of driving on surface street versus freeway, amenability to playing energy conservation games through the information interfaces, and travel and charging behavior affecting the match between miles driven per charging interval and each driver's realized CD range. One measure to encapsulate all of this is the percent of miles driven in CD operation. The particular vehicles used in this project were driven, on average across the households' four-week trials, in CD operation for 53 percent of their total miles; the range across household means was 17 percent to 81 percent. It is unsurprising, but important, that the range within a single household across their charging intervals can be greater, for example, from less than two percent to 100 percent in one household.

4.5 Energy Conclusions

For the cars used in the project, the total energy savings and gasoline (tank-to-wheels) displaced by electricity (battery-to-wheels) are modest in aggregate and highly variable across households. Those households who are closely able to match their travel to (multiples of) their achieved CD range of these PHEV conversions are able to achieve much higher percent of their travel in CD mode and thus greater percentage total energy (gasoline plus electricity) reductions through the substitution of electricity for gasoline. These households achieve higher percentages of CD mode driving because either, their common daily travel is less than their achieved CD range or they had access to away-from-home, and in this case the workplace, charging so that they charged multiple times per day.

GLOSSARY

AFIP	Alternative Fuels Implementation Program
AHS	American Household Survey
CD	Charge Depleting
CPS	Current Population Survey
CS	Charge Sustaining
EV	Electric Vehicle
GM	General Motors
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
IN	Idaho National Laboratory
MPG	Miles Per Gallon
NHTS	National Household Travel Survey
PHEV	Plug IN Hybrid Electric Vehicle

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